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Research on Twist Drills

By C. J. OXFORD, Jr. (From *The Tool Engineer, U.S.A.*, Vol. 34, No. 3, March 1955, pp. 99-102, 7 illustrations.)

ALTHOUGH simple in appearance, twist drills are the most geometrically complex cutting tools in common use. Their complex geometry and the fact that cutting action cannot be seen while the drill is in operation have combined to delay a complete understanding of the fundamental mechanics of drilling. Only recently have the basic mechanics been investigated, resulting in the first rigorous analysis of twist-drill geometry.

By using an apparatus which would quickly stop the cutting, and then carefully sectioning the workpiece, it has been possible to determine the nature of metal deformation during drilling. It was found that the cutting process along the lips is essentially similar to that in other cutting operations. There is the expected shear zone (or plane) and upward elongation of the metal structure in the chip after it passes through the shear zone.

Under the chisel edge or web portion of the drill, metal flow is different. Deformation is severe and complex. The process involved in this region appears to be a combined indenting-cutting-extrusion operation yielding a highly deformed ribbon chip which eventually escapes into the flute. Distortion of the metal structure in this region suggests qualitatively why twist drills require large axial thrust forces.

Analysis has revealed that the effective rake angle of twist drills is positive across the entire lengths of the cutting edges. This is because the cutting edges near the drill centre (not including the chisel edge) have a high inclination to the direction of motion and produce a shearing cut. This means that the chip is deflected through a lesser angle than it would if it flowed normal to the cutting edge, as has been assumed. A plot of effective rake angle along the cutting edge of two $\frac{3}{4}$-inch twist drills of different design, one a regular drill and the other a heavy-duty drill, is shown in Fig. 1. The characteristics of these drills are respectively:— Web-thickness, 0·11 and 0·19 in.; flute lead, 3·77 and 3·30 in.; helix angle, 32 and 35·5 deg.; and point angle, 133 and 133·5 deg. Drilling speed was 250 rpm and feed was 0·013 in. per revolution. Near the web, the effective rake angle is appreciably positive, while the normal (or tool) rake angle is highly negative. This condition may explain why the twist drill develops an overall power efficiency comparable with that of more conventional cutting tools.

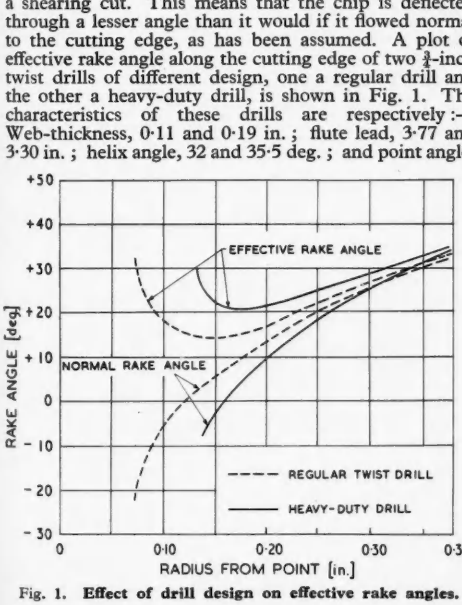

Fig. 1. **Effect of drill design on effective rake angles.**

LIFE OF TWIST DRILLS

The relationship between speed, feed, and twist-drill life appears to be similar to that encountered with other tools, when operated in the usual ranges and with the usual materials where tool life is limited by temperature effects. The classical exponential relationship between tool life T, and cutting speed V:

$$VT^n = C$$

seems to hold. However, when drilling steel with high-speed steel drills, exponent n lies between 0·25 and 0·35 instead of 0·10 to 0·15, as when turning steel with high-speed steel tools. This means that twist-drill life is less sensitive to cutting-speed changes than that of corresponding turning tools.

There is a similar exponential relationship between feed rate and tool life, but the value of the exponent is uncertain, owing to the difficulty of accurately determining the end of life for a twist drill. The end point is even more difficult to determine when feed rate is a variable, since there is some evidence that a somewhat different type of failure is encountered when the feed is either too low or too high. This means that drill feed rates must be held within a fairly narrow range for each size of drill. It is clear that optimum tool life for a given rate of metal removal is obtained by using the highest possible feed resulting in free chip ejection.

When drilling materials with severe work-hardening tendencies, high feeds are mandatory for satisfactory tool life. When drilling S-816, a cobalt-base alloy, with a $\frac{9}{16}$-inch drill, increasing the feed from 0·005 to 0·010 in. per revolution more than doubles drill life.

Because the cutting edges of drills are elastically coupled to the drilling-machine spindle through the drill, drill length also affects life. The principal flexibility is torsional and most of it is in the fluted section. The magnitude of this deflection can be emphasized by noting that a standard drill in the $\frac{1}{8}$ to $\frac{3}{16}$-in. range can be wound through an angle of 60 to 90 deg. before it will break. As the strength of the drilled material increases, the amount of wind-up increases. When variations are encountered in the workpiece, the amount of wind-up changes and, if repeated rapidly, can result in chatter. Rapid changes in torsional loading of the drill are often encountered at entry and break-through, particularly when scale is present.

Destructive torsional chatter may not always be obvious. Fig. 2 is a plot of drill life against flute length with standard-length heavy-duty drills of 0·257 in. diameter at 165 rpm (11·1 sfm) and a feed of 0·005 in. per revolution, using a sulphurized-oil cutting fluid. As the flute length is shortened from $2\frac{7}{8}$ to $1\frac{13}{16}$ in., drill life increases more than 80 times. With ordinary work materials, this effect is not as striking, but a decrease in flute length always increases drill life. Where a long

reach is necessary, a significant increase in tool life is obtained by using a short-fluted drill with a long shank.

When long-fluted drills must be used in tough materials, the web thickness should be increased and the flute space decreased to maintain stiffness. Such drills must be frequently withdrawn to clear chips. The use of a split point or other web thinning is necessary to reduce thrust and to prevent buckling and breakage. The split point also breaks chips into smaller pieces.

Size of Drilled Holes

There has recently been much interest in the actual size of holes produced by drilling. This is of particular importance when the holes are to be tapped and becomes vital if the thread pitch is fine in comparison with the diameter, or if the length of engagement is a small fraction of the nominal screw diameter. Fortunately, for ordinary lengths of engagement, the tap drill size is not critical, if thread height is 60% or more.

To determine the amount of oversize to be expected in normal drilling, the Metal Cutting Tool Institute conducted a series of tests on various sizes of drills operating in steel and cast iron. The results of these tests are summarized in Fig. 3. The centre curve shows the average oversize to be expected and the other two curves indicate the range of oversize variation to be expected. The range of variation indicates that it is generally not possible to compensate for oversize by reducing drill diameters. The values given in the curves can be approximated within about 0·001 in. for $\frac{1}{8}$- to 1-in. drills by the following relations :—

$$\text{Average oversize} = 0{\cdot}002 + 0{\cdot}005\,D$$
$$\text{Maximum oversize} = 0{\cdot}005 + 0{\cdot}005\,D$$
$$\text{Minimum oversize} = 0{\cdot}001 + 0{\cdot}003\,D,$$

where D is the nominal drill diameter in inches.

While the oversize values given are based on cast iron and steel, they apply approximately to most metals, except non-ferrous materials with large thermal coefficients and high production rates. It is possible to have so much thermal expansion of non-ferrous metals that, upon cooling, the drilled hole may actually be smaller than the drill diameter.

It is evident that the two-flute twist drill, as ordinarily used, cannot be considered a precision hole-producing tool. Where size must be held to close limits, a precision sizing operation, such as reaming, must be used.

Performance Variations

Twist drills appear to be more sensitive than most other tools to small variations in tool geometry and in the machinability of the workpiece. Furthermore, there is considerable difficulty in accurately determining the

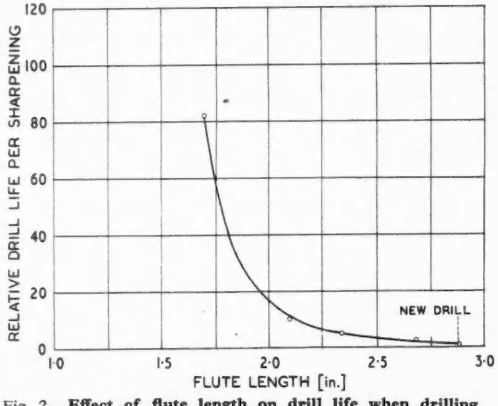

Fig. 2. **Effect of flute length on drill life when drilling S-816 high-temperature cobalt-base alloy.**
The data points are averages for six drills.

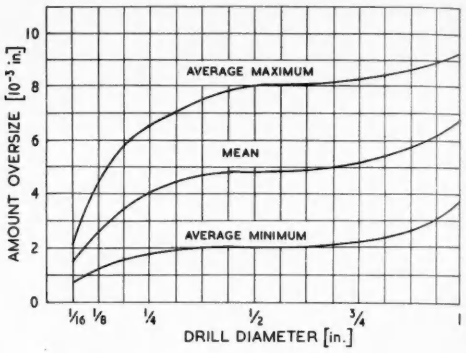

Fig. 3. **Average and range of oversize holes produced when drilling steel and cast iron.**

end of twist-drill life. Types of dulling vary widely, so that wear-land measurements are not reliable. Sometimes, wear develops in such a way that the drill is almost self-sharpening. Power input to the drilling machine increases slowly, until total destruction is reached, and then it increases so rapidly that the machine may not be stopped in time to permit reconditioning of the drill. There is some indication that the increase in drill thrust force may be a good indicator of drill dulling, but this cannot be generally used because it requires a dynamometer. The most used indicator of actual or incipient drill failure is the sound the drill makes.

Drill testing is not hopeless, but fairly long tests involving a large number of drills are necessary. Even with a large number of drills on test, the range of scatter often exceeds $\pm$ 50% of the average value. The results of tests on 296 identical drills run under identical conditions for the first grind showed that the average drill life was about 68 holes, and that the standard deviation range, which included slightly more than two-thirds of the test data, was from 47 to 89 holes, a spread of about $\pm$ 31%.

Since the normal probability curve in connection with these tests appeared to fit the data reasonably well, it can be assumed that most of the scatter of the test results was due to random or accidental factors, including material drilled, coolant, machine set-up, drill sharpening, drill geometry, drill-tool material, drill heat treatment, and uncertainty as to the exact point of failure. Statistical manipulation of the data by test groups indicates that about half of the scatter is due to variations in the drillability of the material drilled, and the remainder can be attributed principally to the drill and uncertainty as to the drill-failure point.

While this discussion is based on carefully controlled laboratory observations, the findings are applicable to operating conditions in shops, except that here the scatter in performance is likely to be greater. There is also a high probability that shop tests involving only a few drills can give misleading results, particularly if the indicated difference in performance is small. When looking for a small difference in performance, 50 or more drills must be tested and the results averaged. Large variations in the drillability of commercial metals must be expected. The effect of material variations on test results can be greatly diminished if the drills being compared can be run on the same workpiece and, if possible, in the same drilling-machine spindle.

The chances of unpredictable drill failure in production can be greatly reduced if drills are not run to failure but are removed for resharpening after drilling two-thirds to three-quarters of the number of holes required to cause average failure. Incidentally, such a practice greatly reduces resharpening costs, since drill damage rises precipitously at the failure point.

Minimising Stress-Corrosion Cracking of Cylinder Valves

By M. SCHUSSLER. (From *Corrosion*, Vol. 11, No. 3, March 1955, pp. 19-22, 9 illustrations.)

The investigation described in this article covers the diagnosis of the cause of splitting of aluminium-bronze bonnets on valves for cylinders used for handling corrosive gases and the remedial steps taken to minimise these failures.

As a result of the susceptibility to failure of a number of forged aluminium-bronze valves, used for handling corrosive gases in cylinders under conditions where high pressures might be encountered, an examination was made on several valves to determine the cause of failure ; in addition, stress-corrosion tests were conducted on new valves to determine if remedial measures might be found which would minimise the possibility of future failures.

Some valves failed in service by developing longitudinal splits in the bonnets. The valves under consideration were of the design shown in Fig. 1 and failed under exposure conditions involving corrosive gases on the internal surfaces and steam and atmospheric impurities on the external surfaces.

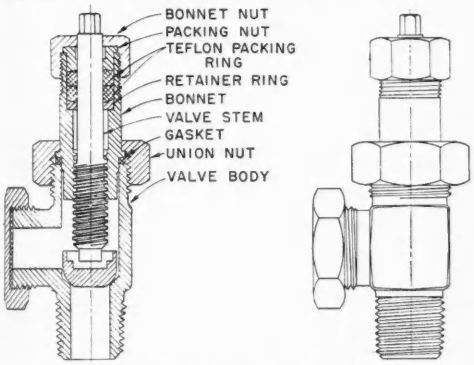

Fig. 1. **Details of 1-in., two-piece cylinder valve.**

The bonnet material was a two-phase, forged or extruded aluminium-bronze, with a nominal composition of 9% Al, 1% Fe. Cross-sections through the failures showed that the path of fracture was intergranular and was typical of stress-corrosion failures. The bonnets (hardness Rockwell B 85) had a two-phase structure of alpha plus eutectoid, with the eutectoid dispersed in long, longitudinal stringers (Fig. 2).

Propagation of the fracture in a longitudinal direction was suspected to have been facilitated by the stringers of the second phase in the material. This contention was verified in stress-corrosion tests. In the test results the longitudinal splits which developed in the bonnets followed the stringers ; even when circumferential ruptures were produced under certain stress-corrosion testing conditions, branch cracks sought out the eutectoid stringers, although the stringers were oriented transversely to the direction of crack propagation.

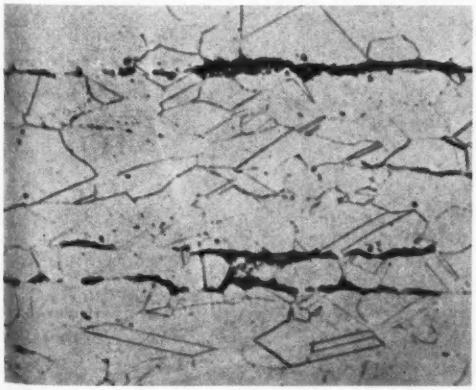

Fig. 2. **Longitudinal cross-section, showing typical structure in as-received bonnets. Etchant : Ammonium hydroxide, hydrogen peroxide. (×250)**

Remedial Treatment of Bonnets

Findings on the bonnet failures indicated that, if the stringers of eutectoid were eliminated, or if the eutectoid was randomly distributed, the valve bonnets would be less susceptible to failure. In an effort to eliminate the eutectoid stringers present in the as-received bonnets, a two-step heat treatment was selected, as follows :—

(1) Transformation of the original alpha plus eutectoid structure to the beta phase by heating for ten minutes at 1750° F, and water-quenching to retain the beta structure.
(2) Reheating to 1110° F, holding for four hours to transform most of the beta phase to alpha phase, and slow cooling, to permit gradual transformation of the remaining beta to alpha plus eutectoid.

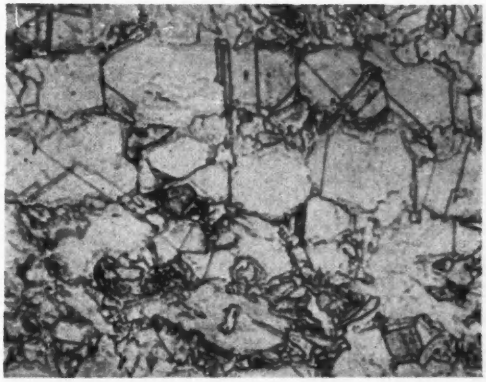

Fig. 3. **Longitudinal cross-section, showing typical structure in heat-treated bonnets. Etchant : Ammonium hydroxide, hydrogen peroxide, followed by ferric chloride. (×250)**

The structure of the bonnets after heat treatment is shown in Fig. 3. The structure (hardness Rockwell B 65) has more alpha and less eutectoid than the as-received structure. Furthermore, the eutectoid in the heat-treated bonnets appears to be distributed randomly.

In order to evaluate the effects of the heat treatment, stressed valve bonnets in both the as-received and the heat-treated conditions were subjected to accelerated stress-corrosion tests, performed according to the standard mercurous nitrate method. It should be emphasised that the mercurous nitrate test is very severe, but is useful in indicating the trend of susceptibility towards stress-corrosion failure. Results from these tests, such as torque values, cannot be applied directly to other corrosive environments, i.e., to conditions of service.

Samples were examined during the tests for evidence of cracks after exposure times of ½, 1, 1½, 2, 2½, 3, 4, 5, 7, 10, 12, and 15 minutes. In tests on the bonnets only, no cracking occurred, indicating that the material in the as-received condition was not sensitive to stress-

corrosion cracking if no external stress was applied. The bonnets with the as-received structure failed by stress-corrosion cracking with torques on the bonnet nut of less than 20 foot-pounds, while the heat-treated bonnets successfully withstood 60 to 80 ft-lb.

Simulated service tests were conducted in which valves were assembled with various torques on the bonnet nut and subjected to exposure to a saturated steam atmosphere for 48 hours. The bonnets with the as-received structure failed by stress-corrosion cracking with a torque of 100 ft-lb applied on the bonnet nut. One heat-treated bonnet was subjected to the saturated-steam test but did not fail at an applied torque of 145 ft-lb ; nor did it fail when allowed to cool and then stressed to 170 ft-lb torque. Subsequently, the valve was disassembled and placed in a mercurous nitrate bath to test for residual stresses ; however, no failure occurred.

Design Considerations

Arrangement of the valve-stem packing under consideration is shown in Figs. 1 and 4. With this design, the Teflon packing is forced radially against the valve stem and the bonnet as the bonnet nut is tightened. The bonnet nut does not overlap or reinforce the bonnet in the area where the packing is exerting outward pressure. The thickness of the bonnet at this area is only about 0·085 in., from the root of the thread to the outer surface. Because of the force exerted by the packing and because of the thin wall of the bonnet, the bonnet tends to become bulged by the high stresses induced in it when the bonnet nut is subjected to torque.

It appeared that the bonnet could be protected from excessive stresses (a) by increasing its wall thickness, and (b) by modifying its design so that the area on which the packing exerts radial force is contained between the packing and the bonnet nut.

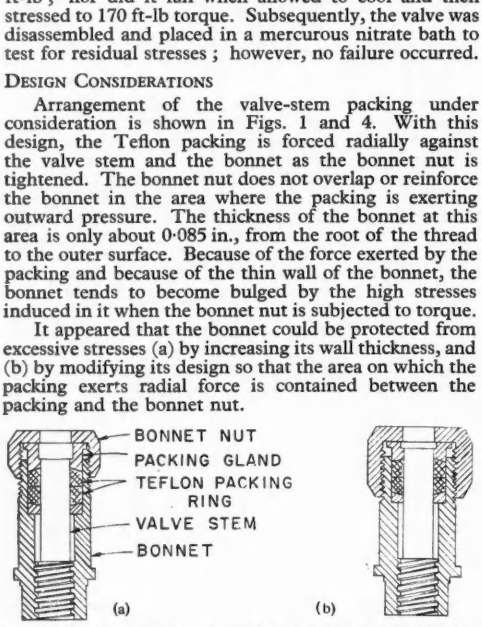

Fig. 4. Details of bonnet assembly on 1-in. type of cylinder valves, showing (a) present design, and (b) modification proposed to minimise stress-corrosion failure in the bonnet and bonnet nut.

This would tend to reduce the tensile stresses in the bonnet to a level lower than that in the original design. These possible modifications to the valve are shown in Fig. 4. It is also to be expected that there would be some stress in the bonnet (i.e., due to torque on the bonnet nut) below which the bonnet would not be susceptible to stress-corrosion cracking.

A series of accelerated stress-corrosion tests was conducted in mercurous nitrate solution on the cylinder valves to evaluate the effect of torque on the bonnet nut and the possible value of modifying the packing and bonnet-nut locations to protect or reinforce the bonnet. When no modifications were made on the locations of the bonnet nut and packing relative to the bonnet, the bonnet cracked during test when as little as 20 ft-lb torque was applied to the bonnet nut ; cracking occurred very rapidly at a torque of 40 ft-lb. The arrangement of the bonnet assembly was then manipulated by cutting down the height of the top packing retainer, so that the bonnet nut engaged nearly all of the threads on the bonnet. Although this resulted in the bonnet nut partly overlapping that area of the bonnet in contact with the packing, the bonnet still cracked in test because it was not fully protected from tensile stresses.

Additional modifications were made by cutting down the thickness of the top packing retainer, so that the bonnet nut engaged nearly all the threads on the bonnet, and by raising the packing entirely within the bonnet nut by using a thicker retainer under the lower packing. This modification appeared to be effective in reducing susceptibility to stress-corrosion cracking, because the bonnet did not fail at torque loadings on the bonnet nut as high as 80 ft-lb, though it should be noted that, at 80 ft-lb torque, the bonnet nut was the more highly stressed member. Several other tests indicated that the bonnet nut was only slightly more resistant to failure than had been the bonnet on unmodified valves. Hence, it was indicated that the thickness of the bonnet nut also should be increased, because the minimum thickness (root of thread to outer surface) of the nuts was only about 0·065-in.

Torque Considerations

In spite of these corrective measures, the stresses developed in the bonnets by the torque applied to the bonnet nut will determine whether or not a bonnet will fail by stress-corrosion cracking. The magnitude of torque that should be applied to bonnet nuts must of necessity represent a compromise. On the one hand, the torque loading should be kept at the lowest possible value, in order to keep the internal stresses at a low level. On the other hand, a minimum torque is required to obtain leak tightness. Because the valves are subjected to a number of thermal cycles during service, the torque applied must be sufficient to maintain leak tightness under these conditions of service life, as well as during the first leak test of the new valve.

Cyclic heating and cooling tests on valves showed that the effective torque on the bonnet nut increases during the heating cycle and decreases after cooling. This is caused by thermal expansion and plastic flow of the Teflon packing. These changes in torque during heating and cooling in service should be taken into account in assembling the valves, to avoid either the development of excessive stresses during heating because of too high initial torque or the possibility of leaks during cooling resulting from too low initial torque. The test results indicated that torque on the bonnet nut in the range of 20 to 30 ft-lb was about optimum with Teflon packing on these valves.

Based on the results of this investigation, the bonnets were heat-treated according to the treatment described above. In addition, the torque applied to the bonnet nut was fixed at 30 ft-lb. Since these improvements have been incorporated, no bonnet failures have occurred with the existing valves.

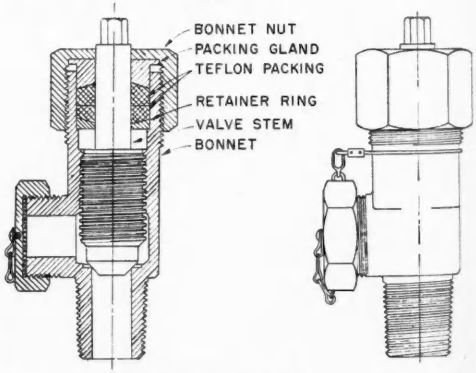

Fig. 5. Details of new design of 1-in., one-piece cylinder valve.

Design modifications found desirable in order to minimise further the possibility of stress-corrosion failures have been incorporated in a new design (Fig. 5) for cylinder valves for future applications.

Investigation into the Load Dependency of Vickers Micro-Hardness

By H. BÜCKLE. (From *Zeitschrift für Metallkunde*, Vol. 45, Nos. 11 and 12, November and December, 1954, pp. 623-632 and 694-701, 20 illustrations.)

In the first instalment last month of this article, existing hypotheses regarding the load dependency of Vickers micro-hardness were discussed, together with indications concerning sources of error, the influence of resolving power, sample preparation, and structure, and the problem of elastic recovery. This concluding instalment deals with the influence of rim formation.

(*Concluded from April issue*)

Influence of Rim Formation

The height of the rim formed around Vickers indentations is usually stated to be from 0·5 to 0·8% of the indentation diagonal. Hitherto, in all hypotheses on the load dependency of micro-hardness, rim formation was not considered. An increase in the rim zone of 1 μ can cause an increase in the diagonal of 7 μ (due to the small inclination angle of 16 deg. of the diagonal).

It is known that, even in cubic crystals, the indentation diagonal depends on the orientation of the crystals and the relative position of the pyramid, combined with a change in the form of the indentation. The characteristic indentation shapes on the (100) plane of a cubic face-centered crystal for two different positions of the pyramid are shown in (Fig. 7); the maximum difference between the diagonals is 10%. For other orientations and pyramid positions, values between 5 and 10% were found, whereby the indentations frequently assume complicated intermediate shapes. These phenomena were hitherto considered to be due to the elastic recovery in relation to crystal orientation, and were even used as a proof of the recovery hypothesis. Closer observation, however, shows that the concave bulging portions have not sprung back, but that in contrast the convex portions are caused by the penetration of the diamond through the bulge of the rim.

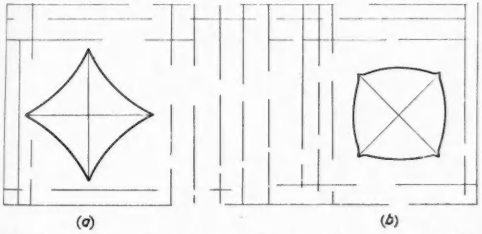

Fig. 7. **Characteristic shapes of indentations on the (100) plane of a cubic face-centered crystal, for two different positions of the diamond.**

Rim formation depends on the symmetry of the slip planes of the crystal. In cubic face-centered crystals the rim bulge preferably follows the fourfold symmetry of the (111) planes, independent of the pyramid position chosen. The four protrusions of the rim bulge always have the same position relative to the crystal, but not with reference to the pyramid, which intersects the bulges more or less deeply, according to the position used. The relationship between orientation, position of the rim bulge, and pyramid position is clearly shown in Figs. 8 to 10. To make the rim formation visible through shadows, oblique lighting was used. The indentation in Fig. 8 corresponds absolutely to that shown schematically in Fig. 7b. For a quantitative evaluation, interference photographs of aluminium and copper were taken by Bernhardt, using monochromatic light ($\lambda = 5350{\cdot}5$ A). In some instances, colour photographs were made, to increase accuracy by finer subdivision of the interference bands. Four indentations in the same grain were made, rotating the pyramid by 30 deg., as shown in Fig. 9. The axis of the diamond pyramid was 1 deg. from the vertical, so as to increase the bulge formation on one side. The position of the bulge is not influenced by the position of the pyramid. Moreover, the various indentation shapes due to the different pyramid positions are made clear.

Valuable information is obtained from Fig. 10, which shows a symmetrical indentation in the (100) plane of an aluminium crystal. The four edge bulges appear to be relatively low (0·4 μ) and not cut by the diamond; the original polishing plane is considered on a level with the diagonal corners. The middle portions of the edges are deeply depressed (1·5 μ). Owing to the incompressibility of the metal, this is difficult to understand, and the displaced volume should be found near the indentation. A quantitative evaluation by means of a planimeter shows that about 10% of the volume of the indentation is situated in the four bulges, the remainder being accounted for by an increase in the level of the surroundings. As confirmed by the formation of slip lines, this raised zone extends to more than twice the length of the indentation diagonal. The raised zone has the form of a truncated pyramid, with a maximum height of 0·6 μ in the middle of the edges, with an inclination of 10 minutes. This small inclination supports the impression that the original level was in the height of the diagonal corners, whereas in reality it is $(1{\cdot}5 + 0{\cdot}6) = 2{\cdot}1$ μ higher. Without the edge bulge the indentation would be a square in the original polished surface. The measurement of the diagonal d_o was too large by

Fig. 8. **Micro-indentations in Nimonic under normal and oblique illumination. (×1000)**

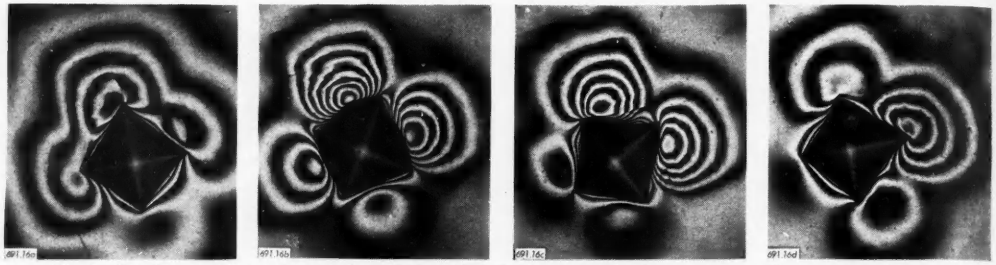

Fig. 9. **Interference photomicrographs of indentations in the same aluminium grain, with successive diamond rotations of 30 deg. (×200)**

$\Delta d = 2 \times 2{\cdot}1 \times \cot 16° = 14{\cdot}6\ \mu$, whereas the sides a_o increase by only $\Delta a = 2 \times 0{\cdot}6 \times \cot 22° = 3\ \mu$. If the correction values from the measured values $d_1 = 103\ \mu$ and $a_1 = 64{\cdot}5\ \mu$ are deducted, $d_o = 88{\cdot}4\ \mu$ and $a_o = 61{\cdot}5\ \mu$, and $d_o : a_o = 1{\cdot}435$ instead of $\sqrt{2} = 1{\cdot}414$, the difference being 1·5%, which therefore favours the bulge hypothesis.

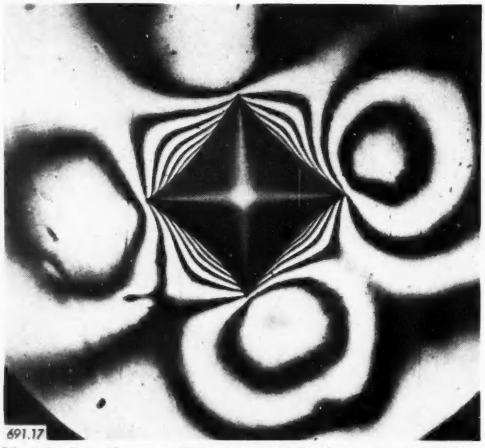

Fig. 10. **Interference photomicrograph of a symmetrical indentation on the (100) plane of an aluminium crystal. (×300)**

This method is somewhat laborious and is not suitable for test series. When using the "effective bulge height" instead of the "absolute" height, a simpler measuring method can be used: Into the star-shaped indentation (Fig. 11) a square is inscribed, which corresponds to the intersection of the pyramid with the original polished surface. The diagonal d_o can be determined directly by measuring the distance a_o of the maximum restriction. With the actual diagonal d, $\Delta d = d - d_o$ and the bulge height $\Delta h = \frac{1}{2} \times \tan 16° \times \Delta d = {}^1/_7\ \Delta d$; the possible error is 0·1 μ or less with careful measurements.

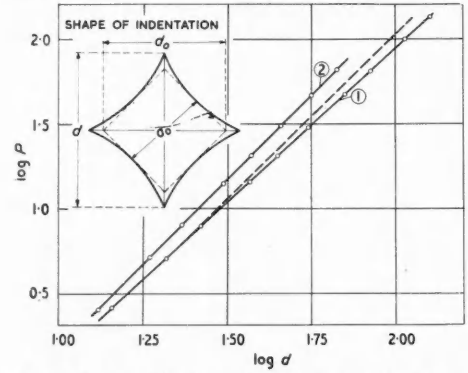

Fig. 11. **Curves of log $P = f$ (log d) measured on indentations of maximum deviation from square shape, based on largest d and smallest d_o diagonal in insert.**
(1) Log $P = f$ (log d); $n = 1{\cdot}95$ to $1{\cdot}76$.
(2) Log $P = f$ (log d_o); $n = 1{\cdot}98$ (constant).

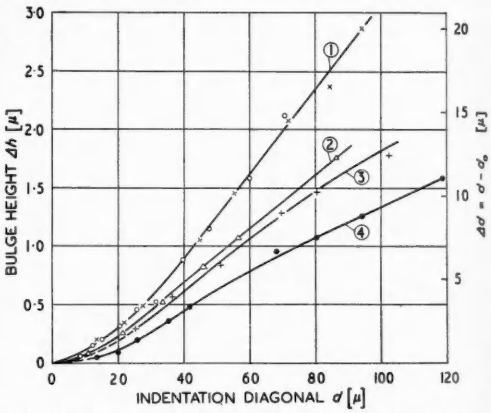

Fig. 12. **Measured differences $\Delta d = d - d_o$ (see Fig. 11), and calculated bulge heights Δh as functions of indentation diagonal d.**
(1) Absolute bulge height for Cu (circles) and Al (crosses).
(2) to (4) Effective bulge height of differently orientated aluminium crystals.

The values d and d_o were measured for a number of indentations for loads from 2·5 to 130 gr, and the curves of log P/log d (curve (1)) and of log P/log d_o (curve (2)) plotted. Curve (1) indicates high load dependency; a tangent to the lower part gives $n = 1{\cdot}95$ and to the upper part 1·76; Curve (2) is practically a straight

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line with $n = 1{\cdot}98$. The indentation diameter d_o in the original polished plane therefore follows Kick's law of similarity. The same result was obtained with a copper crystal. Consequently, the load dependency of the micro-hardness can be ascribed mainly to the influence of the rim bulge and the measured value of the indentation, particularly because the bulge height in the micro-range is not proportional to the indentation diagonal; otherwise, curves (1) and (2) in Fig. 11 should be parallel to one another. Fig. 12 shows the bulge height in relation to the indentation diagonal for the two crystals already mentioned, where the absolute bulge height was measured. The bulge height first increases slowly, and from about 40 μ diagonal length it becomes proportional to the indentation diagonal. The good conformity between copper and aluminium is astonishing and supports the author's opinion that the measured load dependence of micro-hardness is not connected with the elastic but only with the plastic properties of the material. For higher loads, the curves have a different straight-line characteristic and run approximately through the origin. Investigations into the intermediate range, covering the transition between micro- and macro-hardness, have not as yet been concluded.

The shape of the log P/log d curves can be represented by inverse tan functions, which, however, are not easy to use for calculating macro-hardness. There exists, however, no simple, generally valid extrapolation. The use of simplified approximate formulae is discouraged, as their usefulness is connected with conditions which are difficult to check and which frequently do not obtain. For purposes of comparison, the use of fixed reference loads is suggested. For series of measurements, calibration curves are recommended directly relating macro-hardness and the reading on the objective micrometer. Such graphical relationships can be established for a given material, micro-hardness tester, optical system, and test load.

U. S. A.

The Heat Processing of Combustible Material

By C. P. Mann. (From *Mechanical Engineering*, Vol. 77, No. 3, March 1955, pp. 219-222, 6 illustrations.)

It has been customary, in heat processing such combustible materials as textiles, paper products, synthetic fibres, and plastics, to apply the heat at as low a temperature as practicable, in order to avoid the risk of spoilage. This approach, however, results in large, bulky heat-processing equipment, requiring correspondingly long processing times and relatively high labour and maintenance costs.

A newer heat-processing concept of achieving exceedingly high rates of heat transfer, by employing extremely high temperature differences between the applied heat and the work, has shown remarkable results in the heat-treatment of metals and other non-combustible materials. It is now being applied to various combustible materials and is showing significant production economy and product improvement.

Two techniques have been used successfully in a number of cases to adapt this new concept of heat processing to combustible materials, i.e., direct flame impingement, and high-temperature gas-generated radiation.

It has been established that heat processing of many products composed of many combustible materials involves a time-temperature relationship such that the higher the temperature applied, the shorter the processing time. The equipment required for the treatment also becomes more compact.

The two techniques selected for attaining high rates of heat transfer—exposure of the work to direct flame contact, and exposure to high-temperature radiation—are in some respects two of the most convenient means for utilizing heat at higher thermal heads.

Flame-Impingement Process

The flame-impingement application presented in this paper involves the use of gas flames of high heat intensity and uniformity over their entire length, produced by multi-ported burners specially designed to burn a stoichiometric air-gas mixture, forced under pressure through the burner ports. In appearance, the flame is blue and very "stiff," i.e., the flame velocity and rate of combustion are so rapid, and the flame is so securely rooted to the burner itself, that the burner is enabled to give a positive direction to the flame and deliver its heat at the desired location, in spite of extraneous air currents or similar hindrances.

A ribbon burner representative of this type consists essentially of three parts, i.e., the burner manifold to which the air-gas mixture is fed under pressure; the deep burner ports, which in this instance are formed in ceramic material as a heat-insulating barrier between the flame and the manifold; and a ceramic cavity or "tunnel," in which the flame originates and which provides flame-retention qualities of a high order, permitting high rates of combustion of the gases.

Radiant-Heat Process

The high-temperature radiant-heat application involves the radiant-heat energy given off from a ceramic surface, heated by a gas flame. One means of attaining this result is to cause a gas flame to burn along the surface of a heat-insulating ceramic body. A part of the heat of combustion of the gas flame is thereby converted to radiant heat, because the insulating characteristics of the ceramic material cause its surface temperature to rise rapidly to a temperature in the order of 2000° F. The heat is then radiated from this surface to surrounding bodies in proportion to the difference of the fourth powers of the temperatures of the radiant surface and of the surrounding bodies.

Fig. 1 shows one type of gas radiant burner in which a stoichiometric air-gas mixture emerges under pressure through ports at the centre of a cup-shaped cavity of a heat-insulating ceramic body in such a way that, when this gaseous fuel is ignited, it burns completely within the cavity and along the inner surface of the cup. The cup, becoming radiant, transmits its heat by wave motion in the same way as, and at the velocity of, light. This design of burner permits directing the radiant heat, which penetrates intervening air currents without hindrance, at the desired intensity to the work.

Applications of the Processes

Because the heat of direct flame-impingement or high-temperature radiation generated by these burners can be directed to the surface of a film at high intensity and can be controlled accurately within very close tolerances, these methods have been applied extensively and most successfully in the heat processing of polyethylene film to prepare the surface for printing.

The burner equipment is very compact, and mechanisms have been devised for physically moving the burners, when such movement is desired. This movement may be synchronized with process operations, making it possible to start and stop the film without danger of damage, because the high-intensity heat may be applied or withdrawn instantly in response to the film movement.

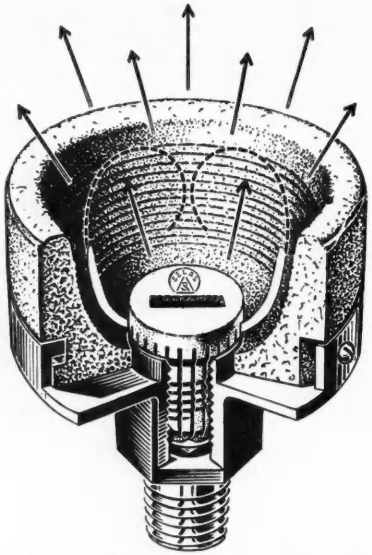

Fig. 1. **Gas radiant burner, in which a stoichiometric air-gas mixture burns within a cup-shaped ceramic cavity.**

Printing on polyethylene film presents a real problem. Until the surface of this material has been treated, it will not retain printing ink. It has been discovered that if only the surface of this film is heated to a temperature of 825° F, a chemical change takes place, making the surface ink-receptive. Subsequent printing will adhere readily, permitting the material to be handled without damage to the printed surface. However, at about 450° F, polyethylene film is destroyed, so the problem is to sear 0·0004 in. of the film surface and yet prevent the remaining body of the film from becoming overheated. This is accomplished in one process by an extremely high-temperature exposure for a fraction of a second.

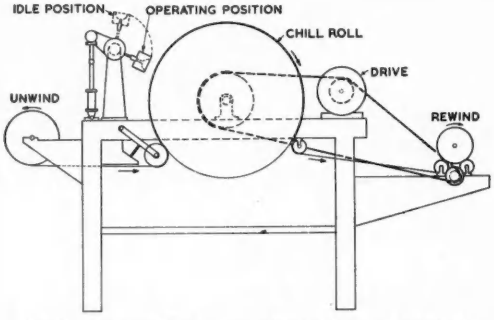

Fig. 2. **Schematic diagram illustrating radiant-heat processing of plastic film.**

Fig. 2 is a schematic illustration of how this heating process is performed. The film is fed continuously at the desired speed and is wrapped around and held in intimate contact with a chilled roll, while at the same time the outside surface of the film is subjected to the high-intensity heat. Physical movement of the burner, actuated by starting or stopping the film, may be effected by rotation of the burner, or by lifting away.

The radiant gas burner described, which enables radiant heat to be directed and distributed uniformly over a plane surface at an accurately controlled high thermal head, combined with a mechanism for mechanically removing this heat very rapidly in synchronism with production-machine operation, has also been applied to the production of imitation leather and to the drying of gummed paper to such good effect that production rates have been increased remarkably and valuable floor space saved.

The flame-impingement method can be used for laminating aluminium foil. In laminating a web of aluminium foil to a paper web, one surface of the aluminium foil is coated with a water-soluble adhesive. This coated side is pressed against the paper web, and the laminate is dried and cooled before it is rewound into a roll for shipment. The direct-flame-impingement burner oven is designed to perform this laminating operation. This is a critical drying operation because, if sufficient moisture is not removed, the bright finish of the aluminium surface will become tarnished while in storage in the roll; if too much is removed, the laminate becomes brittle. This oven has increased the rate of production more than twice for the same floor area and without any increase in labour over the former low-temperature application.

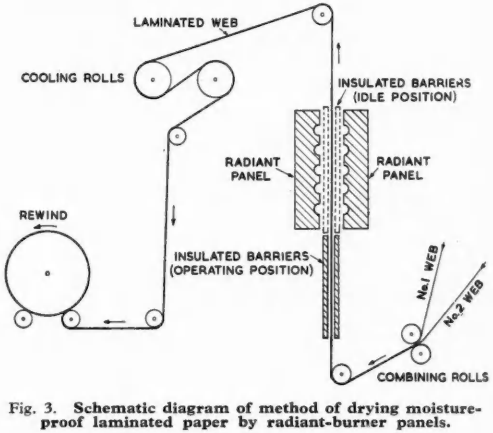

Fig. 3. **Schematic diagram of method of drying moisture-proof laminated paper by radiant-burner panels.**

Another laminating process, shown schematically in Fig. 3, utilizes radiant-burner panels for the drying of moisture-proof laminated paper. Two moistened webs of heavy kraft paper are used, one side of one web being coated with moisture-proof adhesive. The two webs are pressed together by rolls and the laminated web is then heated, to dry the two paper webs and to complete the cementing together of the webs by heating the moisture-proof adhesive. The web is then cooled before being rewound.

The design of this high-temperature heating equipment provides for passing the laminated web exactly between two radiant panels. To avoid destruction of the material when the motion of the web is stopped, insulated barriers (on each side of the web) automatically move upwards, so as to be interposed between the burners and multi-ply web.

Because combustion of the gaseous fuel is completed within the cup-shaped cavity of the burners, these radiant panels can be placed in close proximity to the web, thereby condensing the size of the equipment and conserving floor space.

Unit Radiant Burners

Some radiant burners are built as separate units in three shapes—round, square, and hexagonal. This permits assembly in an almost endless variety of arrangements, providing unusual freedom in design.

Unit-burner construction of this type has been successfully used in bookbinding. After glue has been applied, the books are placed on a conveyor which elevates them and carries them horizontally in front of a line of radiant burners located near the ceiling of the room, leaving clear floor space below. The burners direct their radiant heat on the glued backs and dry them rapidly. The conveyor then carries the books before an air-cooling system, and discharges them to the next operator for rounding and covering. This operation requires but a few moments, instead of the many hours previously required ; it also saves re-handling and floor space.

High-temperature, gas-generated heat also has made it possible for manufacturers of paper and paper products, such as chip-board and roofing felt, to realize significant increases in production, without any increase in floor area or labour costs. In the manufacture of these products, large quantities of heat are used in removing the water which is necessarily embodied in the web as an inherent processing step. The conventional method of evaporating this water is to wrap the web over a succession of steam-heated drums, and thus slowly drive out the moisture. The high concentration of radiant heat, made possible by the complete combustion of the gaseous fuel within the cavity of the radiant burners, enables the burner faces to be located within inches of the wet web, and thus transfer the heat required to evaporate the water at a high rate within a concentrated area.

One of the outstanding examples of heat processing combustible materials by direct flame impingement and by high-temperature radiation is the drying of printing ink on rotary magazine presses. The success of this application is made possible by the ability to concentrate, direct, and control rigidly the application of high-temperature heat, by the ribbon burner and radiant burner described previously. Gas-fired driers emit a temperature of upwards of 2000° F to the paper web, causing almost instantaneous drying of the printed surface and enabling these presses to print up to four colours in daily production at a speed of 1200 fpm. These modern presses use heat at a rate of over 5,000,000 BTU per hr. The resulting increase in production, conservation in floor space, savings in labour, and the tremendous improvement in overall economy made possible through heat processing by these burners

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GERMANY

Forces and Material Flow in Spinning

By E. SIEBEL and K. H. DRÖGE. (From *Werkstattstechnik und Maschinenbau*, Vol. 45, No. 1, January 1955, pp. 6-9, 12 illustrations.)

SPINNING has always been of importance as an alternative to deep-drawing, as tooling up is simpler and cheaper, especially for short runs of components having rotational symmetry. Spinning can be effected in several ways, and the multiple passes required in deep-drawing can sometimes be reduced to a single operation.

In contrast with deep-drawing, which has been the subject of extensive research into stress distribution and material flow, with theoretical principles more or less known, such work is entirely lacking in the spinning process. The stresses are much more complicated, and the derivation of a simple formula comparable with that used in deep-drawing is unlikely, necessitating experimental determination of forces and correlation of model tests, using the principles of similarity.

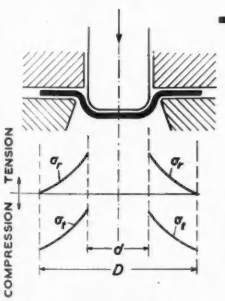

Fig. 1. **Forces and stresses in deep-drawing.**

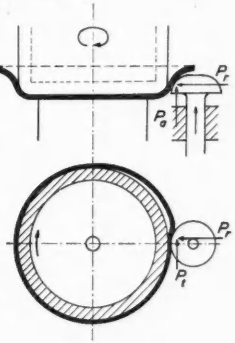

Fig. 2. **Simple spinning process.**

Recounting the stresses induced in deep-drawing and determining how spinning conditions differ, in the cupping draw (Fig. 1) the flat blank is pulled in from an overall diameter D_o to a diameter d as the material is drawn through the die. Tensile stresses σ_r in the direction of draw increase from zero at the perimeter to

$$\sigma_r = k_{fm} \log_e (D/d) \quad \ldots \quad \ldots \quad (1)$$

at the edge of the die, these stresses being in equilibrium with tangential compressive stresses σ_t. At the edge of the blank, $(\sigma_t - \sigma_r)$ corresponds to the compressive strength k, and the material is thus in the plastic state throughout, the plasticity condition $(\sigma_t - \sigma_r) = k_f$ being fulfilled. As a result of σ_t, the plane blank perimeter tends to obtain stress relief through ripple formation, and a blank-holder prevents it from buckling.

Now, suppose that, starting with a flat blank, the same spun shape is required as that obtained by drawing, and a cylinder of diameter d is to be formed with a corresponding tangential shortening of the fibres (Fig. 2).

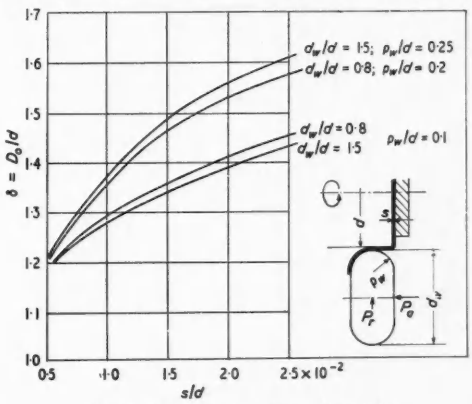

Fig. 3. **Limiting diameter ratios** D_o/d.

As before, corresponding compressive tangential and tensile radial stresses must exist, the pressure-roller contact being localized, in contrast with the die lip contacting the whole perimeter. Again, there is a tendency to ripple formation, but the use of a blank-

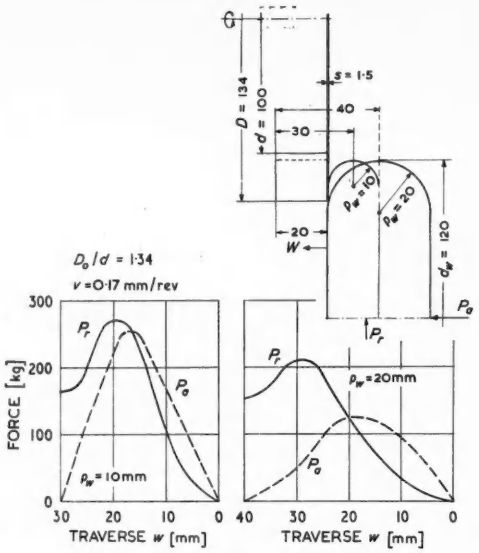

Fig. 4. **Forces involved in spinning.**

holder to guide the edge is impracticable. In deep-drawing, the limiting diameter ratio D_o/d is determined by the stroke, such that the stress at the drawing edge is less than the ultimate tensile strength of the material, whereas in spinning, buckling is the normal limiting factor. The buckling tendency increases as the ratio of cup diameter to sheet thickness is increased, but slow pressure-roller feed supports the blank and materially lessens this tendency. The radius of curvature ρ_w of this roller is important, but the roller diameter d_w has generally only a slight influence on D_o/d.

Limiting Diameter Ratios

The effect of different factors on D_o/d was examined for the spinning of dishes of 100 mm in diameter, and test results are shown in Fig. 3, the materials used being deep-drawing steel, brass, and pure aluminium. All materials, when initially annealed, exhibit the same limiting conditions. There is an increase in D_o/d with increasing s/d where s is the thickness, and also with increasing ρ_w/d, but the roller diameter d_w exerts only a slight influence, and feed per revolution and circumferential speed have no effect at all. All quantities in the diagram are related to d, the diameter of the spinning form, the results being of general application. From the test results, it will be impossible to have D_o/d much greater than 1·5, whereas, in deep-drawing, there is no difficulty in achieving $D_o/d=2$ in a single pass.

Forces Acting in Spinning

Force components are shown in Fig. 2, these being P_a axial, P_r radial, and P_t tangential. P_a and P_r are easy to measure, but P_t is much smaller than P_a or P_r, and must be derived by equating the energy absorbed in rotating the workpiece, and the energy involved in shaping it. As an example, Fig. 4 shows the variation in P_a and P_r when spinning a cup of 100 mm in diameter from 1·5 mm deep-drawing steel. As the spinning roller is fed against the projecting edge, forces rise rapidly, passing through a maximum value. If ρ_w is increased, the lever arm of P_a and the traverse w to complete the process are also increased, but maximum P_a is decreased. At the same time, maximum P_r is virtually unchanged. It may be assumed that P_t is more or less proportional to P_a. To obtain an indication of the magnitude of the tangential force, an expression is derived, giving the work done by P_t in revolutions n corresponding to $w=30$ mm and feed rate $v=0{\cdot}17$ mm per revolution.

$$A=P_t\, n\, \pi\, d=P_t\,(w/v)\,\pi\, d$$
$$=P_t\,(30/0{\cdot}17)\,\pi\times 100=55{,}500\,P_t\ \text{[mm kg]} \quad \ldots \quad (2)$$

which is equivalent to the energy of deformation when rolling the edge of the blank, of width b and thickness s, over the spinning form.

If V=volume of material deformed, η_F=deformation efficiency, k_{fm}=mean stress during deformation, and φ_m is a deformation factor expressed as the natural logarithm of the mean diameter ratio,

$$A=V\,\frac{k_{fm}}{\eta_F}\,\varphi_m=\pi\, d\, b\, s\,\frac{k_{fm}}{\eta_F}\,\varphi_m \quad \ldots \quad \ldots \quad (3)$$

Putting $b=17$ mm, $d=100$ mm, $s=1{\cdot}5$ mm, $k_{fm}=40$ kg/mm^2, $\varphi_m=0{\cdot}17$, and $\eta_F=15\%$, the work of deformation is obtained as

$$A=\pi\times 100\times 17\times 1{\cdot}5\times\frac{40}{0{\cdot}15}\times 0{\cdot}17=365{,}000\ \text{[mm kg]} \quad (3a)$$

Hence, the mean tangential force

$$P_t=\frac{365{,}000}{55{,}500}=7\ \text{kg approx.}$$

Thus, P_t is only a minor factor, increasing in direct proportion with feed rate v, since the total distance of force application is correspondingly reduced.

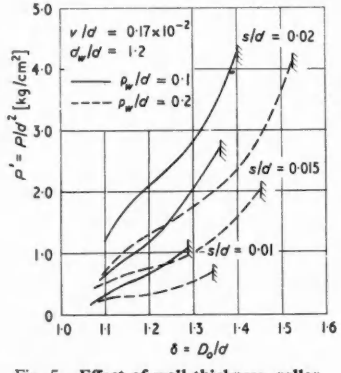

Fig. 5. **Effect of wall thickness, roller curvature, and diameter ratio on maximum axial force.**

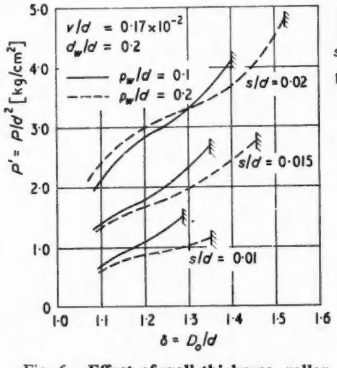

Fig. 6. **Effect of wall thickness, roller curvature, and diameter ratio on maximum radial force.**

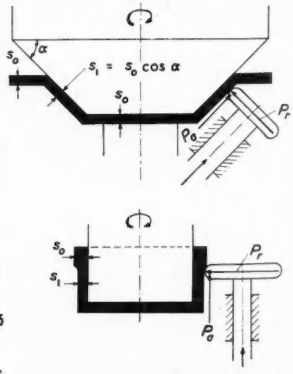

Fig. 7. **Spinning and stretch-forming.**

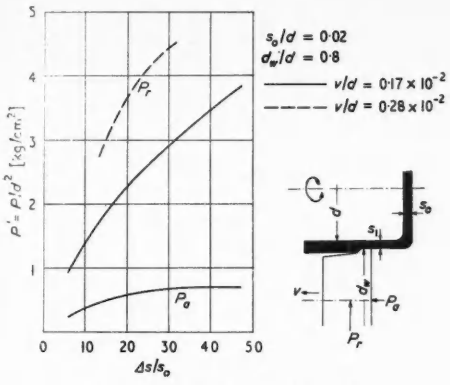

Fig. 8. **Stresses in stretch-forming.**

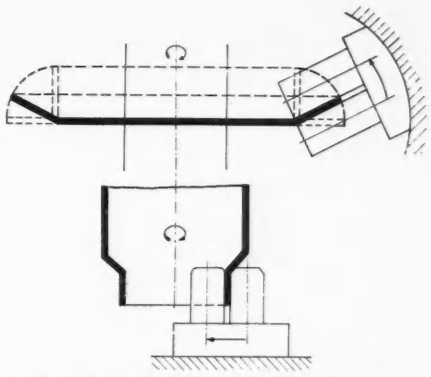

Fig. 9. **Spinning with pressure and counter rollers.**

Fig. 5 shows the effect of $D_o/d = \delta$, s/d, and ρ_w/d on the maximum value of P_a, forces being divided by d^2 to make the results generally applicable, giving the dimensions in kg/cm^2. P_a rises rapidly with increasing values of D_o/d and s/d, the effect of ρ_w/d having already been mentioned. Limiting values of D_o/d are shown.

From Fig. 6, radial forces are seen to be similar to axial forces, but the influence of ρ_w is less in this case. The effect of d_w/d is relatively small, but forces are slightly increased as d_w is increased, because of the larger area of contact between roller and blank. Feed v has little or no effect on P_a, but it has already been shown that P_t is proportional to v.

Stretch-Forming

Apart from simple spinning, in which there is no change in wall thickness between blank and spun shell, stretch-forming or flow turning is a very important process. In normal spinning, deformation is limited by the tendency to ripple formation, whereas in stretch-forming, as shown in Fig. 7, drawing in of the blank edge is avoided in a correctly engineered process. In spinning conical parts, it is essential that the initial thickness s_o be reduced by simultaneous pressing and stretching of the work onto the spinning form to the thickness $s_1 = s_o \cos \alpha$ when the blank edge diameter remains unchanged. For cylindrical walls, an initial dish is made by deep-drawing or by normal spinning, followed by a stretch-formed finish, the normal spinning being limited to the diameter ratios D_o/d shown in Fig. 3. Reduction of wall thickness is practically unlimited in stretch-forming, up to 75% being possible in one traverse if the feed is not too rapid. In contrast, the same deformation in deep-drawing would necessitate two to three passes with intermediate annealing, since induced tensile longitudinal stresses have an upper limit in deep-drawing, whereas in stretch-forming deformation is almost entirely due to radial pressure.

Forces measured in stretch-forming aluminium vessels of 100 mm diameter and 2 mm wall thickness are shown in Fig. 8, and indicate that P_a is small compared with P_r, and that P_r increases rapidly as the wall-thickness reduction ratio $\Delta s/s_o$ increases. P_r is roughly proportional to v, and P_t must be approximately proportional to the reduction of cross-section per revolution $F_d = v\ \Delta s$, according to rules applicable to every rolling process. If η_F is the deformation efficiency of the forming process, then

$$P_t = F_d \frac{k_{fm}}{\eta_F} = v\ \Delta s \frac{k_{fm}}{\eta_F} \quad \ldots \quad \ldots \quad (4)$$

where η_F in stretching should be about 30% to 40%, owing to obstructed material flow.

The same rules apply to stretch-forming tools as in transverse tube rolling. Flow resistance to radially displaced material must be minimized in an axial direction by giving a very small radius of curvature to the forming edge of the pressure roller. A cylindrical guide-cone in front of the stretch-forming edge prevents the workpiece from being lifted off the spinning form.

Spinning Large Workpieces

For components of large diameter, spinning forms become expensive, and a counter roller should be substituted, as shown in Figure 9, with provision for simultaneous displacement of pressure and counter rollers. Tilting rollers of the type illustrated have been used for flanging dished ends of boilers, of from 2 to 3 m in diameter. An arrangement for pulling in the ends of a cylinder is also shown in Fig. 9.

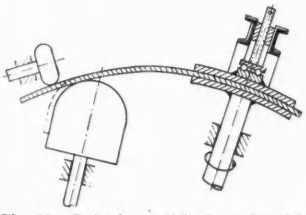

Fig. 10. **Spinning dished end with mushroom-shaped counter roller.**

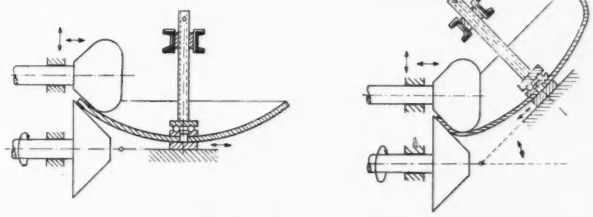

Fig. 11. **Spinning dished ends with shaped rollers and tilting workpiece.**

Figs. 10 and 11 illustrate the manufacture of dished ends, using shaped counter and pressure rollers, the rotating clamp for the predished plate being progressively tilted in the latter case. Owing to the large forces involved, cold spinning is limited to plates up to 15 mm thick, but up to 25 mm can be accommodated in conventional hot spinning. Ends of greater thickness are drawn on hydraulic presses.

The Theory and Construction of Germanium Diodes

By J. C. VAN VESSEM. (From *Philips Technical Review*, Vol. 16, February 1955, pp. 213-224, 12 illustrations.)

GERMANIUM, like silicon, selenium, and tellurium, belongs to a group of semi-conductors which owe their conductivity exclusively to electrons. Semi-conductors in which the charge transport is effected by ions also exist, but belong to another group.

In a crystal of silicon or germanium, each atom is situated at the centre of gravity of a tetrahedron formed by the four adjacent atoms to which it is bound. Each bond between two atoms is attributable to an electron-pair of one valence electron from each atom (a so-called covalent, or homopolar, bond). Thus, the four valence electrons of each atom are all involved in similar bonds. Thermal vibrations in the crystal lattice may eject an electron from its position. However, such vibrations can only release valence electrons, since the other electrons of the atom are bound too tightly to the nucleus. In fact, the probability that even a valence electron will be so ejected is very small, since it must not only have sufficient energy, but the local situation must be such that an escape-path may be formed. This is equivalent to saying that for release to occur it must be possible for the laws of conservation of both energy and momentum to be satisfied. For the same reason, however, the probability that an electron will drop back to the original site when once released is likewise small; it is then virtually isolated. Nevertheless, such an electron tends to linger in the vicinity of the vacant site (or hole), owing to the presence at this site of a non-compensated nuclear charge which attracts it. Because the two charges attracted to one another are in a dielectric (i.e., germanium, where the dielectric constant $\varepsilon_r = 16$), the attraction is weak; even at room temperature, the electron is more or less free to drift through the crystal at random under the influence of thermal agitation.

The holes are also affected by thermal agitation. A hole may easily become occupied by a valence electron from an adjacent bond, leaving another hole at the original site of the electron thus displaced. Again, a valence electron may move into the new hole, and so the process will continue. In effect, then, the original hole roams through the crystal.

CONDUCTIVITY OF PURE SILICON AND GERMANIUM

Given an electric field in a piece of pure silicon or germanium, free electrons and holes will both contribute to the flow of current. The contribution of the free electrons requires no explanation; that of the holes arises as follows:—The holes tend to become occupied by those valence electrons which, in moving into them, submit to the thrust exerted by the field. Since the electrons move against the field, the holes move with it, i.e., they behave like positively charged particles.

The precise conductivity of a material depends, amongst other things, on the number of free electrons and holes in it. Now, the generation of free electrons and holes is continuous but, at the same time, recombination, i.e., the filling of holes by free electrons, is also taking place. In the equilibrium state, the number of charge-carriers generated and the number recombined per unit time and volume are exactly equal. The respective concentrations n (for negative) and p (for positive) of free electrons and holes, identical in pure silicon or germanium, are invariably so small as compared with the concentration of atoms that the rate of generation of charge-carriers is not noticeably affected by the number of valence electrons already released; hence, the rate of generation may be considered as a constant (C). On the other hand, the number of recombinations is proportional to the concentration of free electrons as well as to the concentration of holes, and may therefore be defined as cnp, c being a constant. Accordingly, the equilibrium values of n and p are governed by the following equations:

$$c\,n\,p = C \quad \ldots \quad \ldots \quad \ldots \quad (1)$$

and

$$n - p = 0, \quad \ldots \quad \ldots \quad \ldots \quad (2)$$

so that

$$n = p = \sqrt{C/c} \quad \ldots \quad \ldots \quad (3)$$

The constants C and c are both functions of the temperature; a rise in temperature will produce a sharp increase in C, but only a relatively small increase in c, thus increasing the conductivity. This is a characteristic property of all semi-conductors.

The bond between valence electrons and nuclei is slightly weaker in germanium than in silicon; hence, germanium is the better conductor at a given temperature. In diamond, the crystal structure of which resembles that of silicon, the valence electrons are bound so tightly to the nucleus that the number of charge-carriers generated is negligible. Diamond is therefore an insulator.

The conductivity of germanium, though high compared with diamond, is still quite low. At room temperature, pure copper is roughly 10 million times more conductive than pure germanium.

EFFECT OF "IMPURITIES"

Germanium is adapted to the purpose of rectification by dissolving small quantities of certain elements ("impurities") in it. For example, arsenic is a suitable impurity. The arsenic atom, which can be substituted for a germanium atom in the germanium lattice, has five valence electrons instead of four. Hence, one of these five electrons can find no place in the germanium valence-bond structure and will at first wander more or less at random in the vicinity of the arsenic atom. The latter, having lost one of its electrons, now has a non-compensated nuclear charge. Owing to the effect of the dielectric, the attraction between this positive nuclear charge and the fifth valence electron is rather weak. Even at room temperature, then, thermal vibrations readily free the surplus electron, so that it is in no way distinguishable from others released from valence bonds. Impurities of the same type as arsenic, i.e., those which can supply a free electron, are known as donors. Other donor elements (all pentavalent) are phosphorus, antimony, and bismuth.

The addition of a trivalent element, such as boron or indium, creates an entirely different situation. One of the bonds is then lacking in one electron; hence, there is a vacant site into which an electron from an adjoining bond can move. The energy level of the electron thus transferred is somewhat higher in the new site than in a normal bond, owing to the fact that, in this case, its charge is not compensated by a positive charge in the nucleus, but this extra energy is readily supplied by thermal agitation. A valence electron moving into the vacant site in a boron atom leaves a hole behind. Again by reason of the dielectric, the attraction between the hole and the negative boron ion is weak. Thus, the hole easily diffuses away and so prevents the extra electron captured by the boron atom from returning. Eventually, of course, another hole will approach the boron atom, thereby enabling the captive electron to escape, but on an average the electron will remain in this energetically less favourable position for some time. Because they capture electrons, trivalent impurities are described as acceptors. Acceptors, then, promote the generation of excess holes.

GERMANIUM INCORPORATING BOTH DONORS AND ACCEPTORS

The mechanism of the direct generation and recombination of free electrons and holes as a result of thermal agitation in the crystal, which was tacitly

assumed to be the only active mechanism in the case of pure germanium, is likewise active when both donor and acceptor impurities are present. However, other mechanisms of generation and recombination may be present. Now, a theorem of statistical mechanics states that, if a phenomenon is promoted simultaneously by different independent mechanisms, the resulting equilibrium concentration will be independent of the number or nature of these mechanisms. The existence of more than one active mechanism will affect the speed with which equilibrium is attained but not the equilibrium itself (catalytic action).

Since the concentrations of the impurities are relatively very low (e.g., 1 impurity centre per 100 million atoms), they do not for practical purposes affect the direct processes of generation and recombination. Hence, these direct processes are indeed independent, and the equilibrium concentrations can be computed on the basis of this mechanism alone.

Accordingly, eq. (1) is still valid and can be rewritten :—

$$p\,n = C/c = N_i{}^2 \quad \ldots \quad \ldots \quad (4)$$

where N_i represents the equivalent intrinsic values of n and p in pure germanium.

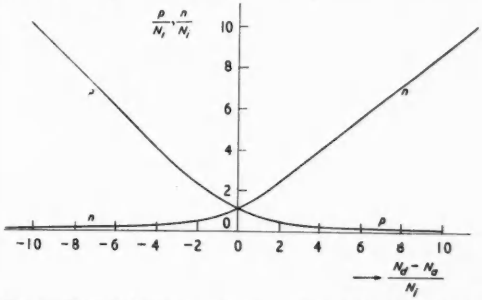

Fig. 1. **Equilibrium concentrations of free electrons (n) and holes (p) in a semi-conductor, plotted as a function of $N_d - N_a$.**

Eq. (2), on the other hand, takes a different form. At room temperature, almost all the donors have produced electrons, and almost all the acceptors holes. Accordingly, the donors and acceptors (concentrations N_d and N_a respectively) are incorporated in the crystal lattice as fixed positive and negative charges, the combined charge-density of which is $N_d - N_a$. The holes and free electrons (motile charges) give a charge-density $p - n$, and, since the crystal is neutral,

$$p - n = -(N_d - N_a) \quad \ldots \quad (5)$$

Eqs. (4) and (5) establish p and n completely as functions of N_i and $N_d - N_a$. In Fig. 1, p and n are plotted against the excess of donors $N_d - N_a$. For both co-ordinates, N_i is taken as unity. Germanium with an excess of donors produces a high concentration of free electrons and a low concentration of holes. It conducts primarily by electrons, and is therefore known as n-germanium. On the other hand, germanium with an excess of acceptors produces a high concentration of holes and a low concentration of free electrons; it conducts mainly by holes (which behave like positive charge-carriers) and is therefore known as p-germanium.

Consider the case of a germanium crystal in which the concentrations of donors and acceptors are so distributed as to create a localized region of transition from p-germanium to n-germanium. The associated variation of $N_d - N_a$, i.e., the difference in the concentrations of donors and acceptors, at such a "p-n junction" will be seen in Fig. 2a. In the following discussion, it is assumed that all the quantities involved depend solely upon the x co-ordinate. Fig. 2b shows the distribution of the concentrations of free electrons and holes corresponding to the local values of $N_d - N_a$ given in Fig. 1.

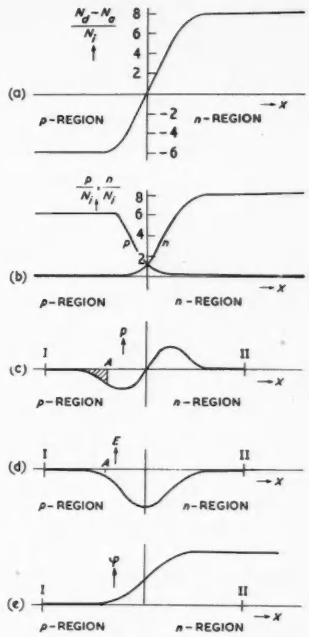

Fig. 2. **Transition from p-germanium to n-germanium.**
(a) Variation of the difference of concentration $N_d - N_a$ between donors and acceptors at a p-n junction. In the p-region, $N_d - N_a < 0$ (excess of acceptors), whereas in the n-region, $N_d - N_a > 0$ (excess of donors).
(b) Variation of the concentrations of free electrons (n) and holes (p) derived from Fig. 1, for the variation of $N_d - N_a$ shown in (a).
(c) Space-charge density arising from the diffusion of free electrons to the p-region and holes to the n-region. The hatched area represents the charge which has crossed section A in the p-region.
(d) Variation of the electric field E within the electric double layer indicated in (c).
(e) Potential at a p-n junction. The electrostatic potential relative to an arbitrary zero level is represented by φ.

This curve is not consistent with a state of equilibrium. A concentration gradient of free electrons and a concentration gradient of holes are set up in the transition zone. These gradients produce diffusion currents of free electrons travelling to the p-region and of holes travelling to the n-region, thus creating a deficit of negative charge in the n-region and an excess of negative charge in the p-region. Accordingly, a region of positive space-charge is formed on the right-hand side of the junction and a region of negative space-charge on the left-hand side; in other words, an electric double layer, roughly as shown in Fig. 2c, is formed. This gives rise to an electric field, which drives the free electrons back to the n-region, and the holes back to the p-region (Fig. 2d). Equilibrium is reached when the electric field is just strong enough to prevent any further diffusion of charges. The above-mentioned electric double layer sets up the potential difference between the n and p regions, shown in Fig. 2e.

The density w_n of the free electron stream in the positive x-direction may be expressed as :

$$w_n = -\mu_n E n - D_n \frac{dn}{dx} \quad \ldots \quad \ldots \quad (6)$$

The first term in the right-hand part of this equation represents the contribution of the electric field (E). This contribution is, of course, proportional to the field and to the concentration (n) of the free electrons. The proportionality constant μ_n is known as the mobility

of the electrons ; the negative sign prefixed to this term is due to the negative electron charge.

The second term in the above equation represents the contribution of the diffusion ; this is proportional, but opposite, to the concentration gradient dn/dx. The proportionality constant D_n is the diffusion constant of the free electrons.

In the case here considered (no applied voltage across the crystal), $w_n = 0$ in the stationary state ; then, from eq. (6),

$$E = -\frac{D_n}{\mu_n}\frac{1}{n}\frac{dn}{dx} \quad \ldots \quad \ldots \quad (7)$$

If φ be the electric potential, $E = -d\varphi/dx$. Considering two sections I and II, one on each side of the transition zone, i.e., one in the p-, and one in the n-germanium (Fig. 2c), and taking n_I and n_{II} as the respective equilibrium concentrations of free electrons at these sections, the potential difference φ_0 between the n-zone and the p-zone can be found by integrating eq. (7) from I to II, as follows :

$$\varphi_0 = -\int_I^{II} E\,dx = \frac{D_n}{\mu_n}\int_I^{II}\frac{1}{n}\,dn = \frac{D_n}{\mu_n}\log_e\frac{n_{II}}{n_I} \quad \ldots \quad (8)$$

Similarly, but taking the density of the hole current as a starting point,

$$\varphi_0 = \frac{D_p}{\mu_p}\log_e(p_I/p_{II}) \quad \ldots \quad \ldots \quad (9)$$

This expression is equivalent to eq. (8) by reason of the fact that, from eq. (4), $p_I n_I = p_{II} n_{II}$ and, in general, $D_n/\mu_n = D_p/\mu_p$, this latter equation being known as the Einstein relation. Putting

$$\mu_n/D_n = \mu_p/D_p = a,$$

eqs. (8) and (9) may be written

$$\frac{n_{II}}{n_I} = \frac{p_I}{p_{II}} = e^{a\varphi_0} \quad \ldots \quad \ldots \quad (10)$$

If ρ be the charge density, ε_0 the dielectric constant of a vacuum, and ε_r the relative dielectric constant of germanium, Poisson's equation in the one-dimensional case here considered is :

$$\frac{d^2\varphi}{dx^2} = -\frac{\rho}{\varepsilon_0\varepsilon_r}.$$

Since $E = -d\varphi/dx$, the above equation may also be written :—

$$\frac{dE}{dx} = \frac{\rho}{\varepsilon_0\varepsilon_r}.$$

Consequently,

$$E(x) = \int_{-\infty}^{x}\frac{\rho}{\varepsilon_0\varepsilon_r}\,dx. \quad \ldots \quad \ldots \quad (11)$$

Accordingly, the hatched area in Fig. 2c is a measure of the field strength at section A. If the space-charge regions expand, as they will if the diffusion predominates over the electric field, the size of this hatched area will increase, since it represents the charge which has traversed the cross-section A ; hence, the field strength at A will increase. On the other hand, the concentration gradients will decrease, since the variation of the hole concentrations and those of the free electrons will become more and more gradual. The diffusion will decrease as these gradients decrease. Thus, the electric field will gain and the diffusion diminish until a state of equilibrium is established. Given a high conductivity, a small field will be sufficient to maintain a steep concentration gradient in equilibrium. The charge layer will then be quite thin. Similarly, if there is a difference in conductivity, as between the region on the left and that on the right of the p-n junction, the spread of the space-charge region will be smallest in the zone of high conductivity. In practice, the thickness of the space-charge regions at p-n junctions is of the order of 1 μ.

Rectification at a p-n Junction

Eq. (7) holds good when no current flows. Accordingly, if the potential difference between n- and p-germanium be increased by an amount $\Delta\varphi$ through the application of a voltage, integration of eq. (7) from section I to section II should produce the result $\varphi_0 + \Delta\varphi$. It can only do so if the equilibrium concentrations of the free electrons and holes change. Using dashed symbols to distinguish modified concentrations from the original concentrations, integration of eq. (7) produces :

$$\varphi_0 + \Delta\varphi = \frac{D_n}{\mu_n}\log_e\frac{n_{II}'}{n_I'},$$

which, with the aid of eq. (10), can be put in the form :

$$\frac{n_{II}'}{n_I'} = \frac{n_{II}}{n_I}e^{+a\Delta\varphi} \quad \ldots \quad \ldots \quad (12)$$

A similar formula holds good for the modified concentrations of holes :—

$$\frac{p_{II}'}{p_I'} = \frac{p_{II}}{p_I}e^{-a\Delta\varphi} \quad \ldots \quad \ldots \quad (13)$$

Moreover, it follows from the neutrality condition that the changes in the concentrations of the free electrons and holes must be equal.
In the case of p-germanium, then :

$$n_I' - n_I = p_I' - p_I, \quad \ldots \quad \ldots \quad (14)$$

and in that of n-germanium :

$$n_{II}' - n_{II} = p_{II}' - p_{II}. \quad \ldots \quad \ldots \quad (15)$$

Eqs. (12) to (15) determine the four modified equilibrium concentrations and are easily solved. If the concentrations as calculated in a given case are plotted as a function of $\Delta\varphi$, it will be seen that a given increase in the potential difference between the n and p regions (say, $\alpha\Delta\varphi = +2$) produces only a small drop in concentration. On the other hand, an equivalent decrease in this potential difference ($\alpha\Delta\varphi = -2$) produces a very considerable rise in concentration. This is by no means surprising, because the values of the concentrations have a natural lower limit ; in other words, they cannot fall below the zero level of the so-called minority charge-carriers (i.e., the free electrons in the p-region and the holes in the n-region). On the other hand, increases in concentration are not so limited. This difference in behaviour arising from a difference in the polarity of $\Delta\varphi$ is responsible for the rectification at a p-n junction.

The process leading to the state just discussed may be envisaged as follows :—If a voltage be applied to the germanium, then initially a current will flow which in the p-region will be composed almost entirely of holes, and in the n-region almost entirely of free electrons. To avoid the complications associated with the end contacts of the crystal, it is assumed that the applied voltage is so regulated as to maintain a constant potential difference $\varphi_0 + \Delta\varphi$ between two cross-sections II and I, situated at positions intermediate between the p-n junction and the end contacts in the n and p regions respectively. If $\Delta\varphi$ be negative, a field exists which urges holes in the p-germanium towards the junction and those in the n-germanium away from it. At the junction itself, the applied field upsets the previous equilibrium between diffusion of holes ($p \rightarrow n$) and the reverse flow due to the spontaneous field, so that a net surplus of holes flows across the junction. In a similar way, a net surplus of electrons flows in the opposite direction. However, this flow cannot persist ; it appears that the holes entering the junction from the p-region and the electrons entering it from the n-region attenuate the double layer at the junction (Fig. 2c) and so reduce the spontaneous potential difference across the junction

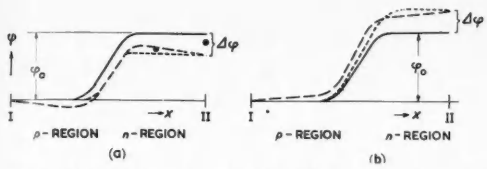

Fig. 3. **Potential as a function of position at a *p-n* junction with an applied voltage, in the absence of generation and recombination.**

(a) Potential of the *n*-region reduced by the applied voltage.
(b) Potential of the *n*-region increased by the applied voltage.

In both diagrams, the curve drawn as a solid line refers to the state before voltage is applied; the potential difference between the *n* and *p* regions is then spontaneous (φ_0). The curves drawn as broken lines apply to the instant when the voltage is applied, and those drawn as dotted lines to the subsequent equilibrium state in which no current flows. A potential level of zero is assumed in Section I.

until there is no longer any potential drop in the *p* and *n* regions outside (Fig. 3a). The field outside the junction is therefore zero, as the whole potential drop ($\varphi_0 + \Delta\varphi$) now occurs across the junction. At the same time, another important effect takes place. The net surplus of holes flowing across the junction from the *p*-region diffuses into the *n*-region and so increases the concentration of holes there. As this increased concentration penetrates through the *n*-region, however, the concentration gradient which drives it gradually diminishes, until all diffusion ceases. The invading holes form a space charge in the *n*-region, but this is rendered ineffective by an influx of free electrons from the opposite direction. A similar process takes place in the *p*-region, where the free electrons now take the part played by the holes in the *n*-region.

Conversely, by reversing the applied voltage, the existing electric double layer is strengthened. The potential jump across the *p-n* junction then increases, again reducing the field outside the transition zone to zero (Fig. 3b). The shortage of holes in the transition zone resulting from the large-scale migration of holes to the *p*-region now produces in the *n*-region a diffusion current of holes flowing towards the *p-n* junction, thus causing a decrease in the hole-concentration in the *n*-region. This decrease penetrates throughout the *n*-region and so reduces the gradient. Eventually, then, the gradient is eliminated altogether and the diffusion current therefore stops. A simultaneous decrease in the concentration of free electrons prevents the formation of an effective space charge. Again, a similar process takes place in the *p*-region, where the holes and free electrons exchange roles.

An important feature of these processes is that the changes in concentration build up in the crystal from the transition zone.

It is by reason of the generation and recombination of free electrons and holes that in reality a current can flow when a voltage is applied across the crystal. When $\Delta\varphi$ is negative, the concentration of holes and free electrons increases, the origin of this increase being the *p-n* junction. From the start of this increase, the rate of recombination will exceed the rate of generation. This is incompatible with a non-conducting stationary state, since the fact that electrons and holes are eliminated more rapidly than they are generated necessitates a constant influx of these charge carriers, i.e., a flow of current.

Similarly, a positive $\Delta\varphi$ produces a stationary state in which regions of relatively low concentration extend from the *p-n* junction into the *p* and *n* regions; in this case, the rate of generation in these regions exceeds the rate of recombination. In a stationary state of this kind, a current must flow to provide an outlet for the excess free electrons and holes generated.

Whether $\Delta\varphi$ be positive or negative, minority charge-carriers are propagated by diffusion, and majority charge-carriers by the electric field. Of course, the electric field also affects the minority carriers, but their concentration is so much lower than that of the majority carriers that an electric field producing an appreciable current of majority carriers will produce virtually no current of minority carriers. For the latter, then, diffusion is the only effective means of propagation. For this reason, it is simpler to consider only the minority charge-carriers and, in fact, this enables conclusions to be reached without considering the more complex behaviour of the majority carriers.

The current in each section is the sum of the free electron and the hole components; hence, this is true, for example, at the section of the *p*-region adjoining the transition zone. Now, the transition zone itself is invariably so narrow that the number of charge carriers generated and recombined in it is negligible. Accordingly, the hole current (produced by the field) in the boundary plane at the *p*-side is equal to the hole current (produced by diffusion) at the *n*-side of the junction. Hence, the total current (hole current + electron current) may be expressed as the sum of the diffusion currents of the minority charge-carriers (electrons in *p*-region and holes in *n*-region) at the two boundary planes of the transition zone.

A diffusion current is proportional to the concentration gradient. If deviation from the equilibrium concentration is large, the rates of elimination and generation of the charge-carriers will also be large and hence a steep concentration gradient will be set up. The diffusion current will then be correspondingly strong. The diffusion currents occurring in the two boundary planes of the transition zone will be appreciably stronger at a given negative value of $\Delta\varphi$ than at the equivalent positive value, i.e., rectification takes place. In the former case, which is the "forward direction," the applied voltage drives holes from the *p*-region and free electrons from the *n*-region to the *p-n* junction (Fig. 3a). When the applied voltage is reversed ($\Delta\varphi$ positive) holes are driven from the *n*-region and electrons from the *p*-region; conduction is then much smaller and in the "reverse direction."

The Formation of *p-n* Junctions

Such *p-n* junctions as are now being considered may occur in several ways. They sometimes occur as a result of a non-uniform distribution of impurities during solidification of a melt of germanium. Again, they may be formed deliberately in many ways, e.g., by adding the desired impurities suddenly to the molten germanium during the process of crystallization.

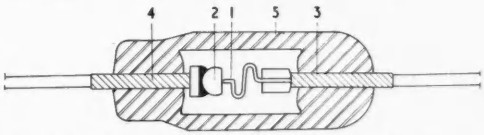

Fig. 4. **Construction of a modern type of point-contact germanium diode.**

(1) Pointed contact spring.
(2) Germanium crystal.
(3) and (4) Supporting pins.
(5) Glass bulb.

For some purposes, crystal diodes are made by establishing a *p-n* junction in a single crystal of germanium. A more common form of the crystal diode, however, is the point-contact diode. It is now generally accepted that rectification in a modern point-contact diode (Fig. 4) is also attributable to a *p-n* junction. After the application of the point-contact to the germanium crystal, several current pulses of high intensity are passed through the diode (a process known as "forming" the contact). This enables impurities to diffuse from the crystal surface or out of the contact spring into the crystal and so form a *p-n* junction around the contact point. The process may also be pictured as an effect of

the current pulses on the local distribution of donors and acceptors near the point, with the formation of a *p-n* junction.

Even without the forming process, any contact between a metal and a semi-conductor will act as a rectifier. No entirely adequate explanation of the mechanism responsible for this rectification has yet been given. Once the contact has been "formed," rectification at the *p-n* junction so established will dominate over any other mechanisms. Fig. 5 shows the rectification characteristics (current as a function of applied voltage) of a point-contact germanium diode before and after forming, v_D being the breakdown voltage, at which $dv/di = 0$. The dotted curve is the characteristic of the diode before the forming process.

As already mentioned, the point-contact is not the only form of *p-n* junction with rectifying properties. However, the capacitative effect of such a contact is small; hence, point-contact diodes offer certain advantages for high-frequency operation. On the other hand, diodes with a *p-n* junction of relatively large area (and consequently higher stray capacitance), are useful for other purposes, e.g., power operation at heavier currents.

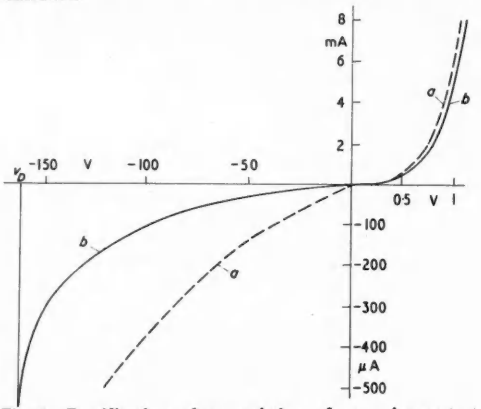

Fig. 5. Rectification characteristics of a point-contact germanium diode (*a*) before forming and (*b*) after forming.

As will be seen from Fig. 5, the leakage current increases with the negative bias until, at point v_D, the dynamic resistance dv/di of the diode is zero. The voltage to produce this effect is known as the breakdown voltage of the diode, since, unless the current be limited by a suitable ballast resistor, breakdown will occur when the voltage across the diode reaches the value corresponding to v_D. The break-down voltage varies between different types of diode. Germanium diodes with breakdown voltages higher than 300 V are occasionally produced, but so far no one has succeeded in producing diodes with this value in a normal production run.

The primary cause of breakdown is heat generated by the current flowing in the crystal. This liberates free electrons and holes, which reduce the internal resistance of the crystal and so increase the leakage current, thus generating more heat; hence, still more free electrons are released and so the process continues until the internal resistance of the crystal is virtually zero. However, if the same voltage be applied in short pulses instead of continuously, this "avalanche" will not have time to develop. According to the above theory, then, the breakdown voltage v_D is higher under these conditions.

In the forward direction, the increase in current with voltage is fairly gradual within the range up to about 0·5 V; beyond this range it is rapid and nearly linear (Fig. 5). The current in the forward direction at 1 volt is usually given as the characteristic quantity for a diode; it represents the average increase in current per volt within the range between 0 and +1 volt. At +1 volt, of course, the actual slope of the characteristic in mA/volt is considerably greater than this average value.

Manufacture of Point-Contact Germanium Diodes

The basic material is spectrochemically pure germanium dioxide (GeO_2), obtained as a by-product of certain zinc ores. It is reduced in a hydrogen atmosphere to pure germanium, which, if necessary, can be further refined by fractional crystallization. At this stage, a pre-determined quantity of a suitable impurity may be added to, and melted with, the germanium. The next step is to divide the germanium into small pieces and to solder them to nickel supporting pins. Special measures are taken to prevent rectification at the contacts formed during this process. The top face of the crystal is then ground smooth; since this grinding seriously affects the crystal orientation of the top layer, the latter is removed by etching with hydrofluoric acid. The supporting pin carrying the crystal is then sealed into a glass bulb fitted with lead-in caps of fernico, and a similar pin carrying a thin spring of tungsten wire is inserted into the bulb from the opposite end so that the spring contact presses firmly against the crystal. The second pin is then also sealed into the bulb. Either a piece of polycrystalline germanium or a single crystal may be employed, according to the particular diode properties required. A considerable improvement of the rectification characteristic is effected by passing several strong current pulses through the germanium ("forming").

The process of soldering the supporting pins in the fernico lead-in caps of the bulb creates a special problem, owing to the fact that the etched germanium surface is readily contaminated by the vapour formed during this process. Such contamination would shorten the life of the diode. For this reason, a protective layer of plastic lacquer, easily pierced by the contact spring, is applied to the germanium surface immediately after the etching process. This layer satisfactorily precludes the above-mentioned effect, without detracting from the quality of the diode. However, in the new type of germanium diode recently introduced (Fig. 4), the metal electrode-holders are sealed direct to the glass. The advantage of this method is that it avoids soldering, and so ensures an exceptionally high degree of stability. On the other hand, for technical reasons, the lead-in pins employed in this process must be thinner than those of the glass-fernico diodes already described; this decrease in pin thickness slightly reduces the heat dissipation from the crystal and so necessitates a slight lowering of the maximum limits for current and voltage.

In fact, the maximum permissible peak and average values of the reverse voltage for this new type of diode are limited to the fixed values 75% and 50%, respectively, of the breakdown voltage as statically measured.

Behaviour of Germanium Diodes at High Frequencies

Germanium diodes are characterized by what is known as the "hole-storage" effect. In a germanium diode operated in the forward direction, a relatively high concentration of charge-carriers occurs in the vicinity of the *p-n* junction. If the voltage applied to the diode be reversed (reverse direction), the leakage current so produced will at first greatly exceed the value indicated by the characteristic, owing to the fact that this relatively high concentration must be reduced to the lower concentration consistent with the normal leakage current.

The average leakage current in the negative period increases with the frequency of the a.c. voltage. In a circuit, then, any increase in this frequency will reduce the detection efficiency and the equivalent attenuation

resistance. This explains the unsatisfactory results obtained when a standard diode is employed, for example, as a video detector. In fact, a special diode in the new series has been developed for such purposes. When so employed, this diode exhibits dynamic properties considerably better than those of the other, statically superior, diodes.

Difficulties from " hole storage " may also occur in the circuits of calculating machines, where it is important to ensure that only pulses of the required square shape are admitted.

Behaviour at High Temperatures

As the temperature rises, more and more electrons are released from the normal bonds. These electrons, and the holes generated with them, increase the conductivity and so reduce the internal resistance of the diodes.

At temperatures in the region of 65 to 75° C, the number of charge-carriers thus generated so far exceeds the number of those introduced artificially as virtually to suppress the differences between standard diodes. It is then necessary, of course, to lower the maximum limit for voltages in the reverse direction, as compared with those valid at room temperature, i.e., up to 25° C. The maximum voltage ratings of diodes of the new series are valid for an ambient temperature up to 60° C; consequently, it will be necessary to reduce these ratings only if the ambient temperature exceeds 60° C.

In general, the ambient temperature of the germanium should be kept as low as possible, and operation at temperatures above 60° C is to be avoided, since rectification, although it does not cease entirely at such temperatures, cannot then be guaranteed.

U. S. A.

Grey Irons for High-Temperature Applications

By J. L. Everhart. (From *Materials and Methods*, Vol. 41, No. 2, February 1955, pp. 90-93, 6 illustrations.)

Grey cast iron is a term covering a series of iron-carbon-silicon alloys mainly having in common the characteristic grey fracture which results from the presence of free graphite. These materials range from irons with tensile strengths of 20,000 psi to high-strength alloy irons with strengths over 60,000 psi.

The term grey iron covers irons that may contain from 2·7 to 3·6% carbon and 1·25 to 3·0% silicon. Alloy irons are grey irons to which sufficient alloying elements are added to improve or modify the properties which can be obtained in common irons. The addition rarely exceeds 2% of any one element and frequently the total alloy addition is no greater than 2·5%.

The as-cast tensile strength of grey irons can be increased only by adjusting chemical analysis to reduce the quantity of free graphite, by changing the size and distribution of the graphite flakes, and by strengthening the matrix by the addition of alloying elements.

In modern foundry practice, inoculation is increasing in popularity as a means of improving grey iron. Inoculants, such as ferrosilicon, are added in the ladle of molten metal to prevent the formation of primary carbides and to promote the formation of normal or randomly distributed graphite flakes. Use of inoculants provides an effective method of obtaining the maximum properties for a given application. They permit utilization of lower carbon-equivalent irons and increase the uniformity of structure and properties.

For elevated-temperature service, chromium is probably the most important of the alloying elements. This element is a stabilizer of carbides and the complex carbides formed do not break down readily at high temperatures. Therefore, growth is retarded and the irons have increased resistance to oxidation. Chromium additions also improve elevated-temperature mechanical properties of the irons because of the stabilizing effect on the structure.

Molybdenum is a mild carbide former and assists in the retention of high-temperature strength. On the basis of the few creep tests which have been reported, molybdenum appears to impart the greatest creep resistance of the alloying elements. However, it does not sufficiently retard growth and therefore is frequently used in combination with a stronger carbide stabilizer, such as chromium. Vanadium is also a carbide former and is effective in retarding growth and reducing distortion.

Nickel is a graphitizing element. In order to retard growth, silicon content must be reduced, chromium must be added, or the nickel must be present in rather large quantities. In amounts sufficient to produce an austenitic structure, nickel is effective in increasing creep resistance. However, this material is in the class of high-alloy irons. Copper is a graphitizer and its effect on the alloy is more pronounced in combination with other elements.

Specifications

Grey cast irons are generally specified by mechanical properties rather than by chemical composition, because different foundries may employ different methods and compositions to produce materials with the same properties.

In ASTM designation A278, seven classes of grey iron are specified to cover requirements of pressure castings for high-temperature service. These classes, ranging from 20,000 to 60,000 psi minimum tensile strength, are coded by numbers indicating the strength; thus, No. 20 indicates the 20,000-psi class. Only the three top classes, 40, 50, and 60 are designated as suitable for service above 450° F, and an additional requirement is a stress-relief heat treatment. Chemical composition is subordinate to properties in these alloys, but maximum carbon equivalent is 3·8% for service above 450° F. (Carbon equivalent = total carbon + 0·3 (silicon + phosphorus)). Alloying elements may be used to stabilize the structure or to facilitate development of desired properties. Common alloying elements suggested for this purpose are chromium, copper, molybdenum, nickel, and vanadium, and any combination can be used.

The ASME code for unfired pressure vessels sets maximum permissible stresses for cast iron based on classes similar to those covered in ASTM designation A278. The code states that the design pressure for vessels constructed of cast iron shall not exceed:—(1) 160 psi at temperatures not greater than 450° F for vessels containing gases, steam, or other vapours; (2) 160 psi at temperatures not greater than 375° F for vessels containing liquids; (3) 250 psi for liquids at temperatures less than their boiling point at design pressure, but not exceeding a temperature of 120° F; and (4) 300 psi at temperatures up to 450° F for closures which do not form a major part of the pressure vessel. However, vessels constructed of stress-relieved material conforming to classes 40, 50, and 60 can be used for design pressures of 250 psi at temperatures of 650° F, if the walls are uniform in thickness. This code does not permit the use of cast-iron vessels as containers for poisonous gases or liquids or inflammable substances.

The ASTM has also designated three classes of grey iron for high-temperature service under conditions in which pressure is not involved. The classes are specified in Designation A319 by carbon equivalent and the basic classes can be further modified with specified chromium contents. In addition, all classes can be modified with such elements as copper, molybdenum, nickel, and vanadium in any combination, to increase strength or resistance to oxidation and surface deterioration. The specifications are general and cover cast irons normally used for non-pressure service up to 1400° F.

Properties

Temperature can affect cast iron in two ways, i.e., deterioration caused by chemical or structural changes, or changes in mechanical properties. The former results in dimensional changes, accompanied by loss of strength and an increase in brittleness. The latter is a phenomenon common to all materials.

The permanent increase in volume which can occur in grey iron subjected to cycles of heating and cooling is called growth. In unstabilized iron, growth is directly related to the maximum temperature reached and the number of heating and cooling cycles involved. In extreme cases, grey iron has been known to increase as much as 50% in volume, although this is not a common phenomenon.

Growth produces a permanent increase in dimensions and can cause severe loss in strength and increased brittleness. Because of these effects, plain grey irons are frequently limited to a top temperature of about 850° F, unless the service is not particularly critical. Under ordinary service conditions, growth rarely occurs at temperatures much below 1000° F in well-made irons of proper composition. On the other hand, certain corrosive agents, such as superheated steam, can cause serious growth at lower temperatures. Thus, each application must be studied individually.

To control growth, unalloyed or low-alloy grey iron should be held to medium-carbon contents with a maximum carbon equivalent of 3·9%. Silicon content should be low. For service up to 450° F, the minimum strength should be 35,000 psi and this should be increased progressively with increase in temperature. The use of small quantities of alloying elements to stabilize the structure is also advisable at higher temperatures.

An investigation into the effect of such small alloying additions has shown that chromium is the most effective growth inhibitor, while vanadium, boron, and copper are progressively less effective, in the order named. Growth starts at about 1000° F and the rate increases markedly at 1600° F. A chromium content of about 1% retards growth to about 1400° F. Irons showing the greatest growth also showed the greatest loss in strength and hardness.

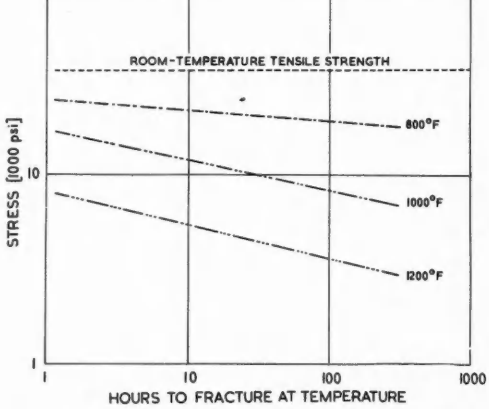

Fig. 1. Stress-rupture data for a low-alloy grey iron.

Investigations into the effects of temperature on the mechanical properties of grey iron have been somewhat hampered by the variety of materials which are included in this category. However, some effects seem to be fairly well established as applicable to most grey irons.

Short-time elevated-temperature tensile tests show that there is little loss in strength up to about 800° F. However, at higher temperatures, loss in strength is rapid. In one test, a cast iron which had retained its room-temperature tensile strength to 800° F lost 60% at 1100° F. Stress-rupture data for a low-alloy grey iron are given in Fig. 1. Constant load at temperature was applied until failure occurred, typical elongation at fracture being from 2 to 3% of the total. Fatigue strength also remains practically constant up to 800° F but decreases sharply above this temperature. Grey cast iron does not seem to be notch-sensitive at elevated temperatures.

This phenomenon of loss in strength above 800° F may possibly be correlated with structural changes. In extended service at temperature, decomposition of the pearlitic matrix in common grey iron starts at about 800 to 850° F and increases in rate at higher temperatures. In one test, holding at 1050° F for 500 hr caused the complete decomposition of pearlite. In another test with special alloy iron, little change resulted. Tests at room temperature after prolonged heating at elevated temperatures show that the mechanical properties deteriorate in common irons held at temperatures above 800° F.

Creep data are not plentiful Available information indicates that a grey iron having a carbon equivalent of 3·9% or less can sustain loads of 10,000 psi at 750° F, without exceeding a creep rate of 1% in 10,000 hr. This figure is probably conservative, since some tests have indicated that this rate would not be exceeded greatly at 850° F.

Applications

Many varieties of grey iron are used at elevated temperatures and no one composition can be specified for any application.

As pointed out previously, both the ASTM and the ASME have set a limit of 650° F and 250 psi for cast iron in pressure service, and many codes follow their lead. This has undoubtedly restricted development of cast iron for high-temperature service. Prolonged applications of common grey iron in steam engines at 750° F and 250 psi pressure indicate that the codes are extremely conservative. Furthermore, internal combustion engines, operating generally at 750° F but reaching a maximum of 1000° F, have functioned satisfactorily for long periods, even though there is a marked temperature gradient owing to external surface cooling.

Some reports of service life of grey iron of unspecified composition indicate the value of this material. In the range of 450 to 600° F, aircraft piston rings last 20,000 hr, and locomotive and diesel-engines parts give an average service of over 20 years.

In the 600 to 750° F range, the average service life of autoclave inserts is 8 years, and of locomotive steam piping 10 years.

In the 750 to 1000° F range, reports have indicated that diesel-engine exhaust valves, furnace tuyères and hearths, and locomotive grate supports have a service life of from 5 to 15 years, while that of lead and zinc melting kettles ranges from 2 to 10 years.

Above 1000° F, hot-forming dies have produced from 4000 to 10,000 parts per grind, while furnace parts such as dampers and grates have service lives up to 6 years, and diesel-engine heads up to 3 years.

British Industrial Developments

DUST CONTROL IN SMALL TOOLS

For some time, Holman Bros. Ltd., of Cornwall, who already have an outstanding record in dust research in connection with rock drills for mining, have been working on another aspect of the dust problem, i.e., dust control in small tools, such as the grinders and hammers operated by compressed air and used for cleaning castings and other foundry work.

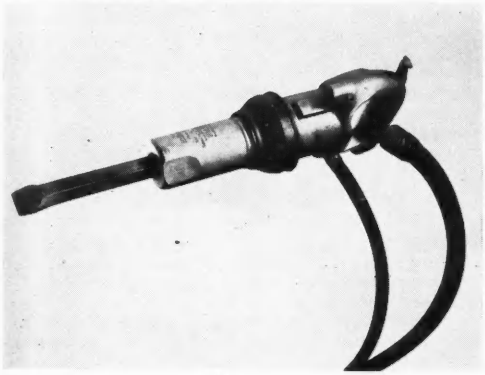

Fig. 1.

After a detailed investigation of the behaviour of dust in grinding, including cinematographic methods of studying airborne dust, a system of suction jacketing, working as part of the normal air system in the case of pneumatic tools, has been designed, and techniques based on the method (called the Dustuctor system) have now been applied successfully to several small tools.

While it is true that various methods of dust control have previously been tried, none has, until now, been wholly satisfactory, for the simple reason that most of these methods attempt to collect the dust after it has escaped from the point of origin. In the Dustuctor system, the method has been to deal with dust as near to its source as possible, and to design the dust-suppression apparatus as an integral part of the tool itself. The trade name of Dustuctor will cover the various applications worked out.

The Dustuctor system has now been successfully used with chipping hammers (Fig. 1), with surface and radial grinders (Figs. 2 and 3), with bench grinders and larger types of swing grinders, and with an operator's glove.

Fig. 2.

In the case of grinding wheels, air economy is important and the Dustuctor method employs a low-volume, high-velocity system. This means that, rather than using a large flow vaguely, the suction is employed in a concentrated manner at certain selected points. The method finally employed used a depression of 15 in. of mercury, applied by means of a close-fitting shroud. Inside this is an additional cowl which follows the top half of the wheel, and in which suction points are incorporated. This serves to strip the top half of the wheel of its boundary layer of highly concentrated dust. Suction is from a venturi type of Eductor, which can be used to supply a number of tools. For pneumatic tools the suction readily forms part of the normal system. For larger electrically driven tools, such as swing grinders, it is possible to use a centrifugal fan or vacuum pump. Furthermore, as it is important that the operation of the tool should not be affected, the present type of Dustuctor cowl has a cut-away base which gives full freedom to the operator when using the tool. This integral system provides a great saving in cost, compared with the usual method of high-volume dust extraction.

Fig. 3.

For the chipping hammer, the problem is somewhat different. The method adopted is to suck the dust through the centre of the tool from holes situated at either side of the tool near its point. This makes use of the observed characteristics of the dust to follow the line of the tool (a course which normally takes it straight to the operator's face). The hollow-chisel method used is a modification of the normal chipping hammer, to enable the dust to pass through the centre of the mechanism.

Another method successfully adopted by F. H. Lloyd & Co., Ltd., Birmingham, using the Dustuctor system, employs a glove for the operator's left hand, incorporating a suction jet which can be held near the point of the origin of the dust. This has the advantage of being easily applied to any normal chipping hammer

Holman Bros. Ltd. have worked closely with H.M. Inspector of Factories, both in providing research facilities and in collaborating on the investigations. Work is still proceeding on dust suppression with various tools. The Company is now able to offer a consultant service to those industries interested in the application of the new system.

HARD SOLDERING ALUMINIUM AND ALUMINIUM ALLOYS

In the development by the Sheffield Smelting Company Limited of the Thesscal process for providing a new and improved method of joining aluminium and aluminium alloys, research in their laboratories was directed at fulfilling the essential requirement of making corrosion-resistant joints, and the mechanism of such corrosion was studied in great detail. The Thesscal process satisfactorily fills the gap between soft soldering at 250° C or less and brazing at approximately 600° C.

Two solders were developed. These are Thesscal " A " and Thesscal " P.12," which have been approved by the Ministry of Supply to Specifications DTD 900/4367 and DTD 900/4398 respectively, after extensive tests at the R.A.E., Farnborough, of the corrosion resistance of soldered joints between aluminium and various aluminium alloys. They are the first solders to be approved by the Ministry of Supply for joining aluminium and its alloys.

Thesscal " A " hard solder has a melting range of 420° C to 450° C and is used with flux No. 92. Its main application is on sheet metal and fabricated forms of aluminium and its alloys. This is a free-running solder, and the technique of joining is very similar to silver soldering. Thesscal " P.12 " hard solder has a longer

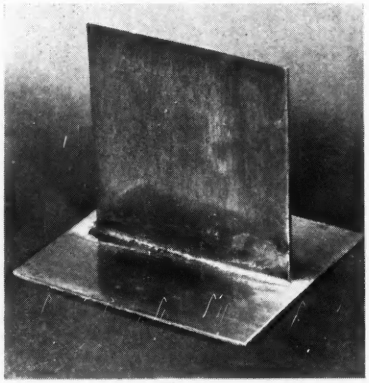

Fig. 4.

melting range, i.e., 440° to 510° C, and is also used with flux No. 92. It is not as free-running as Thesscal " A " and can be moulded much like plumbers' solder. Its use is principally for aluminium casting alloys, to repair broken castings, to build up lugs and protrusions, to join castings to sheet metal, and to fill in blow holes or incorrectly positioned drill holes.

Thesscal solders produce strong, corrosion-resistant joints, and have been tested for corrosion resistance by the well-known standard accelerated tests used by industrial laboratories and by the Aluminium Development Association to assess the corrosion resistance of joints.

Fig. 4 shows a duralumin to aluminium joint made with Thesscal " A " on $\frac{1}{16}$-in. sheet. Note the neat joint line. Fig. 5 shows the same joint after hammering. The aluminium parent metal has cracked, but the joint line is completely unaffected.

In addition, salt-spray tests have been made by the Ministry of Supply prior to the granting of approval, and industrially by Metropolitan Vickers Electrical Company Limited, and also by Rolls-Royce Limited. Humidity tests lasting nine months have been made at the Radar Research Establishment, Malvern. Thesscal-soldered joints passed all these tests satisfactorily. Furthermore, sets of soldered joints have been exposed outside in the industrial atmosphere of

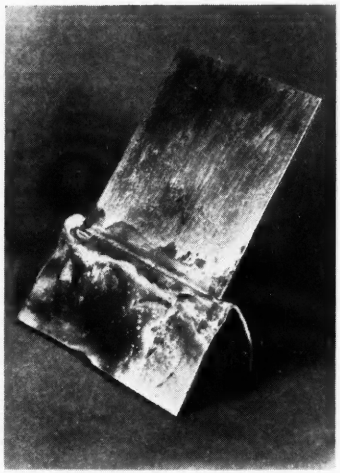

Fig. 5.

Sheffield for more than two years, and the joints are still mechanically sound. Fig. 6 shows a specimen of aluminium joined to aluminium after two years' exposure. The joint is still intact after bending.

The technique of application involves heating with a simple hand torch, using any combination of gases, such as air-coal gas, oxy-coal gas, oxy-hydrogen, and oxy-acetylene. It is being used successfully in the research and production departments of many industrial firms, Ministry of Supply factories, universities, and research organizations. Mass-production techniques of Thesscal hard soldering, such as with electro-gas, furnace, high-frequency, dip, and salt bath, are being investigated, and research to this end is being carried out by the Sheffield Smelting Company, in conjunction with industrial users.

The field of application of the Thesscal process is very wide. A complete range of aluminium alloys can be joined successfully, including aluminium-manganese, aluminium-magnesium, duralumin, and casting alloys, including L.33. These alloys can be joined to one another and to copper, brass, phosphor bronze, tungum, gun-metal, nickel, nickel silver, steel, and stainless steel.

One important use is for equipment and for unstressed or lightly stressed parts in aircraft, where the low operating temperature of about 450° C for Thesscal " A " solder enables thin sheet and sections of duralumin to be joined by unskilled labour without fear of fusion. One aircraft manufacturer has used the process for joining Alclad duralumin for elevator tips, where thin-gauge duralumin has replaced welded joints

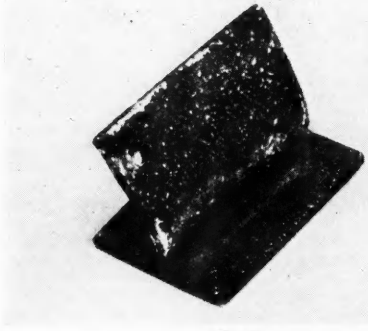

Fig. 6.

previously used in aluminium, which had to be of much thicker gauge to give the required strength. This has resulted in a considerable saving in weight.

Brazing cannot be used on thin-gauge duralumin because of the danger of fusion, since the melting point of the brazing alloy is too near the melting point of duralumin. The lower operating temperature of the Thesscal process enables such thin-gauge aluminium to be joined by unskilled operators with complete confidence. Moreover, the risk of distortion is greatly reduced, and in most cases is completely removed.

Other examples of applications where the process can be used to advantage are heat exchangers for aircraft and guided missiles, and for joining a variety of equipment for radar, medical, domestic, and industrial service. Furthermore, as dissimilar metals can be joined successfully, many new possibilities are opened up, and design departments can take advantage of this unusual combination to produce lighter and stronger components. Similarly, in the foundry, castings and patterns of aluminium and its alloys can be repaired, built up, or corrected with greater ease, since the only equipment necessary is a simple hand torch, and strong corrosion-resistant joints are assured.

INSTRUMENT CASES

Many new models have been added to their well-known standard range of instrument cases and racks by Alfred Imhof, Ltd., of London.

Fig. 7.

With these additional models, Imhof's are now in a position to offer an "off-the-shelf" delivery of 29 different cases, 12 different racks, 5 different control consoles, 15 chassis, 22 panels, 24 handles, and many other accessories. All these cabinets, which are notable for their clean, modern lines, are of the highest quality, design, and finish and offer electronic manufacturers immediate availability in quantity, thus saving many months of production delays and enabling them to concentrate their energies and facilities on making electronic equipment. Furthermore, there are no tool costs to pay.

A typical control console is illustrated in Fig. 7.

THREE-STAGE AIR-COMPRESSOR PLANT

Recently, a three-stage air compressor was supplied by Williams & James (Engineers) Limited, of Gloucester, to the Société Anonyme Belge de Constructions Aéronautiques (SABCA), for installation in one of their plants at Haren, near Brussels. This concern is engaged in the construction of aircraft and the manufacture of special equipment such as undercarriages and other hydraulically operated units. The air compressor has been installed for the testing of airborne hydraulic equipment, such as that fitted to the Hawker "Hunter" Fighter, which they are manufacturing for the NATO Defence Forces.

The plant, which consists of two separate compressor units mounted on base-plates, a control panel, and two sets of air receivers, has an output of 6 cfm (free-air) at a maximum pressure of 3500 psi. One compressor is a two-stage, double-throw, single-crank, water-cooled machine, one cylinder having a bore of 3 in. (first stage) and the other a bore of $1\frac{1}{16}$ in. (second stage). The stroke of this machine, which is driven through guarded V-belts by a 5-bhp electric motor, is 3 in. The other compressor unit is a single-stage, water-cooled booster (third stage), with a bore of $\frac{5}{8}$ in. and a stroke of $2\frac{1}{2}$ in. This unit is driven through guarded V-belts by a $2\frac{1}{2}$-bhp electric motor. The control panel includes coolers, air dryer, electrical contactors, and pressure switch.

The two water-cooled coolers are supplied with moisture traps to allow the moisture, condensed from the air as it is cooled, to be drained away. One cooler operates after the first stage of compression, the other after the second stage. The Watford-type pressure switch controls the 5-bhp motor through an automatic contactor; the operating range of this pressure switch is 800 to 1000 psi. The pressure switch is connected to the two air receivers shown in Fig. 8 on the left of the panel, and also operates a solenoid, which exhausts the air from the pipes between the first- and second-stage cylinders and from the pipes connecting the second-stage cylinder and the air receivers.

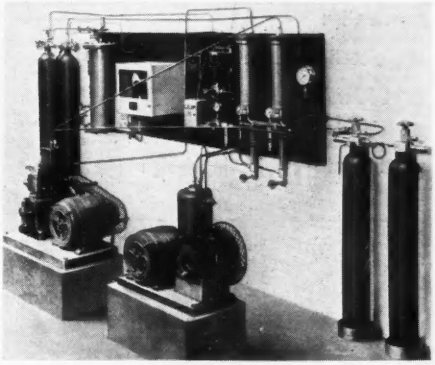

Fig. 8.

The air, after being compressed to 1000 psi, enters the air receiver nearest the panel and thence through a Birlec "Lectrodryer" to the second air receiver, whence it can be extracted in a very dry state at a pressure of 1000 psi. Compressed air (obtained from another source) at a pressure of 15 psi is passed through a re-activator unit, where it is heated, and thence through the contents of the Lectrodryer, in the opposite direction of flow to that taken by the air discharged by the second stage of compression of the plant. Thus, there is a constant supply of air available at a pressure of between 800 and 1000 psi and, up to this pressure, the plant is fully automatic.

When air at 3500 psi is required, the booster unit is switched on and air is drawn from the second air receiver through a pressure-reducing valve to the suction side of the booster. The pressure-reducing valve is included to ensure that the pressure of the air entering the booster is not higher than 600 psi. After compression in the booster, the air is fed to the two 0·33 cu ft air receivers shown on the right-hand side of the panel. Each of the four air receivers is fitted with a moisture drain tap for cleaning purposes.

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CLASSIFIED ABSTRACTS

Numerous important abstracts which, for lack of space, cannot be published in our main editorial columns are regularly included in condensed form in this section. Subscribers may obtain photostat copies of all original articles at cost.

BALL AND ROLLER BEARINGS

Some Design Factors of Ball Bearings and Roller Bearings at High Speeds.

By A. FOGG and J. S. WEBBER. (From an advance copy of a paper submitted to *The Institution of Mechanical Engineers, London*, April 1955, 18 pages, 28 illustrations.)

THE investigation described in this paper arose from the desire of the war-time Ministry of Aircraft Production for information concerning the behaviour and endurance characteristics of ball bearings and roller bearings running in the speed range of the aircraft gas turbines which were, at that time, in the experimental stage. The research was carried out on bearings of the sizes common to these early gas-turbine designs, i.e., of between 1½ and 3 in. bore, and some of the unusual test conditions quoted are actual operating conditions of gas-turbine bearings then being used.

Although surface fatigue has been quoted as the normal mode of bearing failure in more orthodox applications, in practice there are many other causes, among which may be mentioned mechanical inaccuracies in manufacture giving rise to high local stresses, inclusions in the bearing material, pitting due to the passage of an electric current through the bearing, cage failure due to rubbing on the other elements or to centrifugal stress, and inadequacy of lubrication. Some of these troubles can usually be eliminated either in the drawing office or in manufacture. There is reason to believe also that a not inconsiderable proportion of the early failures in gas turbines was due to faulty assembly of the bearings into the engines.

Although primarily concerned with aircraft gas-turbine operating conditions, this investigation has indicated the behaviour to be expected from small (about 2-in. bore) ball bearings and roller bearings when operated under more general conditions of high speed, load, and temperature. It has shown that, in many cases, bearings virtually of manufacturers' standard design will operate satisfactorily under conditions far in excess of those normally applied, whilst in other cases various problems which may arise can be solved, or at least their seriousness considerably reduced, by relatively little modification to design or method of operation. In particular, for those ball-bearing applications where heat generation is a serious problem, considerably reduced operating temperatures can be achieved by changes to the track curvature of the races, by attention to detailed cage design, and, to a lesser extent, by changes in the diametral clearance.

In the case of roller bearings, the extremes of operating loads, speeds, and temperatures which have been satisfactorily sustained are quite remarkable, whilst the striking success of a cageless roller bearing has been demonstrated. On the other hand, it seems that there is little prospect, because of the fundamental problem of metal fatigue, of obtaining satisfactory behaviour from large bearings (of the order of 5-in. bore) under correspondingly higher loads and at the same high speeds, but further work in this direction is desirable. The modifications made to standard bearings during the course of these experiments have provided a better understanding of the basic mechanism of operation of both ball bearings and roller bearings.

CORROSION

The Cathodic Protection of Ships Against Sea-Water Corrosion.

By L. T. CARTER and J. T. CRENNELL. (From a paper presented at a meeting of the *Institution of Naval Architects, London*, April 6, 1955, 22 pages, 17 illustrations.)

THE corrosion of steel in sea water is an electro-chemical process. Owing to differences in electrical potential, currents flow between the more reactive areas (anodes) of the steel surface and less reactive areas (cathodes), causing the metal to pass into solution at the former. When the dissimilar areas are minute and the reaction is more or less uniform over the surface, there is a state of general corrosion, causing rusting to about the same depth all over. The wastage rate of hull steel, if left unpainted and exposed to sea water, would normally be about 0·003 to 0·006 in. in depth per year, depending on exposure conditions. A more serious form of corrosion is pitting, which is a localized action penetrating more rapidly and much deeper into the metal.

Perhaps the commonest cause of pitting is the presence on the hull of an incomplete coating of a material less reactive (i.e., more cathodic) than the steel. Areas coated with paint are normally cathodic to bare spots, and pitting is often found where paint has been damaged, or at "holidays." Millscale is a notable example of a coating which is strongly cathodic to steel, and its low electrical resistance facilitates galvanic action. The intensity of the corrosion depends on the relative areas of intact scale and bare steel and, if the latter is small, intense local pitting may occur.

Cathodic protection is a means of stopping corrosion by suppressing galvanic cells by a current passed to the hull from external anodes, thus making the whole immersed hull surface cathodic. Current may be obtained by using active anodes of a baser metal, or from an external supply through inert anodes. Various types of anodes for each method have been used, the most common being magnesium alloy and steel anodes respectively. The adequacy of cathodic protection in preventing corrosion is guaranteed if the electrical potential of the hull is maintained by adjustment of the current at about 0·8 to 0·9 volt negative to a standard silver electrode.

Various applications of cathodic protection to ships and other structures are described in this paper, a particular example being that of ships laid up in reserve. The pros and cons of applying the process to active ships are examined. Reference is made to special problems in connection with cathodic protection, including the effect on bottom paint and fouling, the application of cathodic protection in fresh water and to aluminium, and the use of zinc protectors.

ELECTRIC MOTORS

An Equivalent Thermal Circuit for Non-Ventilated Induction Motors.

By R. L. KOTNIK. (From *Power Apparatus and Systems (A.I.E.E.), U.S.A.*, No. 16, February 1955, pp. 1604-1608, 4 illustrations.)

A GREAT deal has been written on the subject of motor heating. Most of this material, however, deals with very

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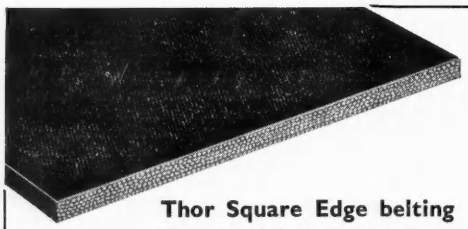

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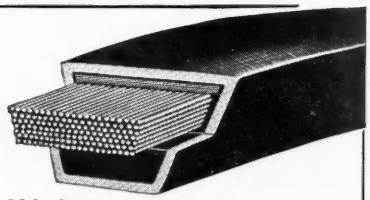

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large motors and generators, a field in which the trial-and-error method of building machines cannot be tolerated. Relatively little has been done towards developing accurate and comprehensive methods for calculating the heating of smaller machines, i.e., machines in National Electrical Manufacturers Association (NEMA) frame sizes 180 to 505.

It is apparent that a method of predicting the temperature rise of machines built in NEMA frames 180 to 505 is needed. To be of real value, the method should give results of an accuracy consistent with that of the other aspects of motor design, and the order of complexity should not be such as to rule it out as a practical adjunct to the standard electrical design. In addition, it would be highly desirable to make the method flexible enough to be adaptable to the calculation of temperature rise during intermittent-duty operation. The method described in this article is intended to cover normal-slip machines having no effective rotor or stator ventilating ducts, and built in NEMA frame sizes ranging from 180 to 505. The method, as developed, is intended primarily for steady-state heating conditions ; however, reference is made to adapting the method to handle thermal transients.

The particular circuit developed appears to represent quite well the thermal circuit of a totally enclosed non-ventilated induction machine of the general NEMA frame size mentioned above. The circuit represents the complete machine, and it is felt that the addition of thermal generators materially aids in making the circuit more comprehensible. Furthermore, tests have indicated that the accuracy of the simplified circuit (overall about 4%) is comparable with the accuracy with which machine losses can generally be calculated. Actually, ordinary heating tests cannot be conducted with a great deal more accuracy than this.

The circuit is not particularly complex, nor are the calculations at all arduous. The calculation of the equivalent circuit could certainly be made a part of the standard electrical design and, with a standard line of motors, many of the circuit constants could be tabulated for ready reference. Moreover, the circuit is fairly flexible and could be easily adapted to machines other than the non-ventilated types. By simply changing the method of calculating the frame temperature, the circuit can be made to represent the fan-cooled machine. Open motors present more of a problem, and undoubtedly the simplified circuit would have to be modified to some extent. Placing capacitors in the circuit, to represent thermal storage elements, would render the circuit capable of handling intermittent-duty machines.

FLUID MECHANICS

A Theoretical and Experimental Study of Shock-Tube Flows.

By I. I. GLASS and G. N. PATTERSON. (From *Journal of the Aeronautical Sciences, U.S.A.*, Vol. 22, No. 2, February 1955, pp. 73-100, 34 illustrations.)

DURING the past ten years, the shock tube has achieved recognition as the most important facility for the investigation of numerous fundamental problems in non-stationary fluid mechanics. The shock tube has been applied successfully to the studies of the transition through shock waves and contact fronts, wave interactions, flows in the subsonic, transonic, and supersonic flow régimes, wave diffraction and refraction, condensation effects, sound-speed measurements, shock loading of structures, relaxation phenomena in gases, flame propagation, chemical kinetics, boundary-layer growth and shock-wave attenuation, atomic physics of states behind strong shock waves, and magneto-hydrodynamics. Thermodynamic states of short duration are available with a range of physical quantities from nearly absolute zero pressures, temperatures, and densities to high pressures, densities, and temperatures, the latter being of the order of tens of thousands of degrees Kelvin.

The purpose of the present paper is to give an integrated account of the shock tube and some of the recent theoretical and experimental studies of shock-tube flows. The reported data for real flows are based mainly on the one-dimensional, non-stationary research work conducted at the Institute of Aerophysics during the past five years. Included are theoretical and experimental investigations of the origin problem, total-shock-wave attenuation, normal shock reflection, simple and double shock-wave refraction, head-on collision of shock waves, head-on collision of shock and rarefaction waves, and the overtaking of two shock waves. In addition, qualitative experiments are presented on normal reflection of rarefaction waves, double refraction of rarefaction waves, head-on collision of rarefaction waves, head-on collision of shock and wire screens, and the emergence of shock and rarefaction waves from the open ends of a shock tube into the free atmosphere.

A comparison is made between theory and experiment, and deviations are discussed. Where a theoretical treatment is lacking, the experiments are analysed qualitatively and the flow quantities, determined from wave-speed measurements, are indicated.

INTERNAL COMBUSTION ENGINES

Fuel Requirements of Small High-Speed Diesel Engines.

By G. M. BARRETT and H. G. FREESTON. (From a paper presented at a meeting of *The Institution of Mechanical Engineers, London*, April 5, 1955, 8 pages, 11 illustrations.)

THE output of the diesel engine is limited by acceptable exhaust conditions, and at maximum speeds the necessity for achieving efficient mixing of fuel and air will undoubtedly call for high standards of fuel atomization, probably combined with fast air movement. As the specific power will be determined by the degree of air utilization, considerable attention must be paid to the avoidance of unused pockets of air to make the diesel engine competitive with the gasoline engine.

For high thermal efficiency and acceptable exhaust temperatures it seems essential that the major part of the combustion should take place close to top dead centre. This requirement calls for an operating cycle closer to the Otto cycle than the diesel cycle. Assuming that 30 deg. crankshaft is allowed for injection, ignition delay, and the major portion of combustion, this means that at 4000 rpm there is approximately 1 millisecond available to complete these processes. Thus, the cycle must be approximate to that of the gasoline engine, but with the advantage of higher compression ratio. In view of the very limited time for completing the injection and combustion processes, the ignition delay must be reduced to a minimum, either by mechanical design, by using suitable fuels, or by a combination of both. Once the flame has been initiated, the remainder of the fuel must be injected at a high delivery rate. Thus, the dynamic injection period must be relatively short, preferably not over 20 deg. crankshaft.

Extensive tests by the authors of this paper have led them to believe that a separate combustion chamber is the most suitable for this type of engine. The excellent economy at part load and the advantages over the gasoline engine are attributed to the high expansion ratio and to the inverse relationship of load and thermal efficiency. Consideration is given to fuel requirements, and results of tests are given. The distributor-type fuel pump is considered to be better than the in-line jerk pump. Methods of eliminating vapour lock when using the more volatile fuels are suggested, and recommendations for the ideal fuel given.

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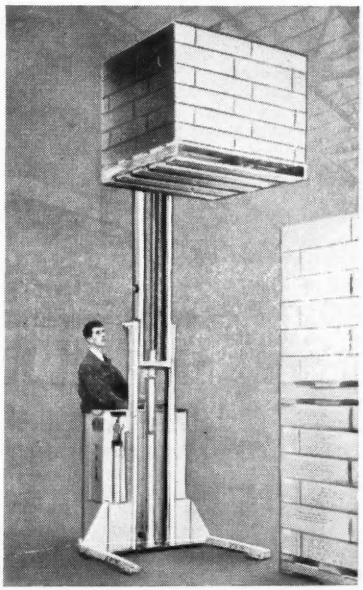

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PLASTICS

Effects of Time, Temperature, and Environment on the Mechanical Properties of Polyester-Glass Laminates.

By B. B. Pusey and R. H. Carey. (From *ASTM Bulletin, U.S.A.*, No. 204, February 1955, pp. 54-58, 6 illustrations.)

The purpose of this paper is to present some experiences in the evaluation of low-pressure laminating resins for structural applications. Emphasis is placed upon one type of test which has proved to be very effective for evaluating resins, reinforcements, and resin-reinforcement interface reagents. In this work, an attempt is made to integrate the factors of time, temperature, and environment upon the mechanical strength of six reinforced plastic laminates.

As described in this paper, the tensile, compressive, and flexural properties of these six representative polyester-glass fabric laminates have been determined over a temperature range from 23 to 100° C. It was found that increasing temperatures produced a reduction in compressive and flexural strength which was greater than the reduction in tensile strength. Increased temperatures erased the presence of an initial " proportional limit " in tension. Representative stress-strain curves are given for several temperatures, and it is shown that strength is more affected by temperature than is modulus of elasticity.

Stress-rupture data for six resin-glass laminates are given, and show that the long-time strength is considerably less than the strength as determined by short-time testing procedures, and also that there is considerable difference between resins. Stress-rupture data in a water environment (stress-corrosion rupture) show that the presence of water reduces the permissible long-time stress still further and also that, here again, there is a considerable difference between resins. For structural design purposes, the stress-corrosion-rupture stress at 1000 hr is a more realistic value than the tensile strength. Stress-corrosion-rupture results may be extrapolated to determine design stresses for longer service life. Data determined in this way are useful in designing structures which are subject to continuous stress in the presence of water.

SMOKE ABATEMENT

The Prevention of Smoke from Heating Boilers.

By T. F. Hurley and L. J. Flaws. (From *Journal of the Institution of Heating and Ventilating Engineers, London*, Vol. 23, April 1955, pp. 1-25, 19 illustrations.)

When a layer of fresh coal is thrown over the top surface of a hot fuel bed, the coal, after the preliminary stage of heating and drying, decomposes as the temperature rises, and the volatile matter, which in bituminous coals often comprises one-third of the total weight, is evolved in the form of tarry vapours and gases. If the conditions are such that the tarry vapours are not burnt and the temperature of the furnace is comparatively low, they will be discharged from the chimney in the form of brown " distillation smoke." On the other hand, if they are further heated without being burnt completely, possibly as a result of insufficient oxygen being present for their combustion, they will be " cracked " to form lighter hydrocarbons and soot, which will either be deposited on the surface of the boiler or carried up the chimney in the form of black smoke. It should be noted that the solid particles of soot formed by cracking are particularly difficult to burn and this makes it desirable to avoid forming them by bringing a partly burnt flame into contact with a cold surface, where it will be chilled and extinguished.

In this paper, some of the problems associated with the production of smoke and its prevention are discussed, making use of the results of experimental work carried out at the Fuel Research Station on different types of boiler commonly used by heating engineers, i.e., a hand-fired Lancashire boiler, a hand-fired vertical boiler, and two sectional heating boilers fired mechanically with coal and oil respectively. It is shown that the amount of smoke produced is influenced by the design of the combustion chamber and firing equipment, by the type of fuel, and by the method of operation.

Curves are given correlating smoke density with such factors as flue-gas composition and thermal efficiency. These show that the production of smoke is accompanied by a loss of thermal efficiency and a consequent waste of fuel, most of this waste being due to the presence of combustible gases in the flue gases. Maximum efficiency was always obtained with the minimum quantity of excess air consistent with the production of a barely visible smoke.

In general, smoke can be prevented by establishing conditions such that all the constitutents of the fuel are completely burned in the combustion chamber. In the case of hand-fired boilers, this can usually be achieved by fitting special fire-doors, enabling controlled supplies of air to be admitted over the fuel bed. With an underfeed stoker a relatively small quantity of smoke was produced, provided that the plant was correctly operated and not overloaded. With correctly installed oil-firing equipment it was easy to avoid visible smoke completely.

SURFACE FINISH

Surface Examination by Reflection Electron Microscopy.

By J. S. Halliday. (From a paper presented at a meeting of *The Institution of Mechanical Engineers, London*, April 15, 1955, 7 pages, 12 illustrations.)

Recently, there has been renewed interest in the method of reflection electron microscopy as a means of examining surfaces. It was in 1933 that Ruska made the original attempt to form images of metal surfaces by directing a beam of electrons at the surface and focusing those which were scattered. Although the resolution was poor, it was later improved by von Borries and Janzen (1941) to about 1 micro-inch, which is as good as that generally obtained to-day. However, with the development of the replica techniques for the examination of surfaces with the electron microscope, the method fell into disuse and only very recently has it been revived. It now appears that, for the examination of certain types of surface, the method has advantages over others already established and it seems particularly suitable for the study of the surface texture of metals finished by the better engineering methods.

In this paper, an examination of surfaces prepared by grinding, lapping, and abrading is described, and it is shown that quantitative measurements can be made of the asperity sizes and of their maximum angle of slope with respect to the mean surface level. An example of the use of the method as a research tool in mechanical engineering is also given.

Micrographs of various metals show that ground surfaces of comparable roughness may have different textures and these differences appear to be related to the mechanical properties of the metals. The range of surface finish which can be examined is illustrated by micrographs of electropolished aluminium which, over large areas, is flat to about 0·1 deg. and on which the highest asperity is 0·4 micro-inch, and of ground hardened tool steel with asperities up to 70 micro-inches high and sloping at 30 deg. to the general surface. The method is suitable for the examination of surface damage by wear processes, and the surface damage on copper after passage of a steel slider is illustrated. Finally, the advantages of reflection electron microscopy over other methods of surface examination are discussed.

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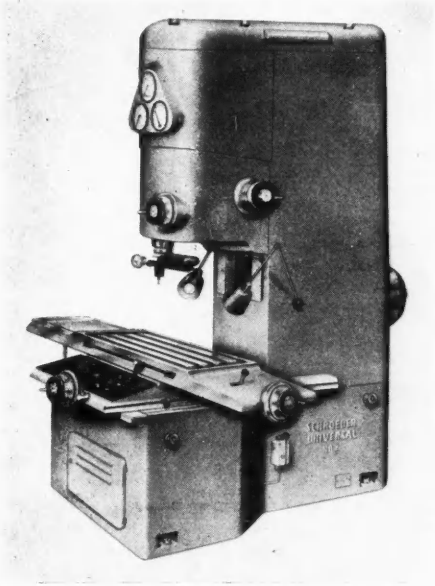

For efficient operation of the 5-hp main motor, a separate fan is used to keep motor temperature at a low level. The centralized electrical power control panel is conveniently located, and entire electrical control is achieved by a single master switch with only three operating positions. The draw-out, package type of chassis, with the magnetic amplifier and all other electrical elements, is located in the lower part of the housing, and can be replaced in a few seconds, facilitating inspection, service, and maintenance.

CABLE ECCENTRICITY GAUGE

An improved cable eccentricity gauge has been added to their range of eccentricity and size-control equipment for extruded wires and cables by the Addison Electric Co., Ltd. of London, W.10. This new model is based on a capacitive method, in which two self-aligning electrode arms lightly touch the cable under test, eccentricity being indicated by a moving-coil meter. The latter is calibrated directly in per cent eccentricity. The meter has full-scale deflections of $\pm$ 25%, with a centre zero, permitting a readability to about 0·5% eccentricity, referred to the wall thickness of the dielectric.

As opposed to the earlier Model 155, which operates on an inductive principle, there is no need for the injection of a pilot current into the cable under test; the latter must, however, be dry while being measured. Two units may, if required, be employed, with their electrode arms at right angles.

MULTI-PURPOSE STUD- AND ARC-WELDING POWER UNIT

Newly introduced by the Crompton Parkinson Stud Welding Organisation, of London, S.W.9, is a transformer rectifier unit which has been specially developed to meet the requirements of both stud welding and manual arc welding. The unit provides a choice of three outputs—one for stud welding up to $\frac{1}{2}$ in. diameter studs; another for single-operator arc welding with current up to 400 A; and a third for two independent arc-welding operators using up to 200 A each. As a new power source, it would therefore appear to fulfil a long-felt need, particularly inasmuch as selection of output is rapidly accomplished by means of a three-position switch and facilities are provided for independent remote control of arc-welding currents.

The new power source consists basically of a 3-phase air-cooled transformer suitable for input voltages of 210/250 V and 360/440 V and for operation on a 40/100 cps supply; two banks of selenium rectifiers, which can be operated either in parallel or independently, according to the position of the selector switch; and two magnetic amplifiers, which facilitate fine control of current when the equipment is used for arc welding. This latter feature, in conjunction with two continuously variable rheostats connected by 20 ft of cable, enables the operator to make accurate adjustment of the current at the point of welding.

The cooling system of the equipment is particularly effective, the rectifier, transformer, and other internal components being maintained at a safe operating temperature by means of a totally enclosed fan. The fan incorporates a centrifugally operated switch which, if the motor ceases to operate for any reasons, automatically interrupts the exciter supply, thereby reducing the output to a safe level. Other important features include the so-called "hot start," i.e., a 25% current increase which occurs momentarily at the commencement of arc welding and provides for easy striking of the arc, and the fact that the unit is a non-inductive power source, with the result that its current-recovery time is comparable with that of an arc-welding transformer.

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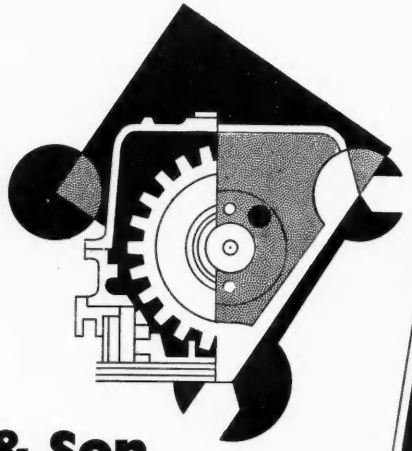

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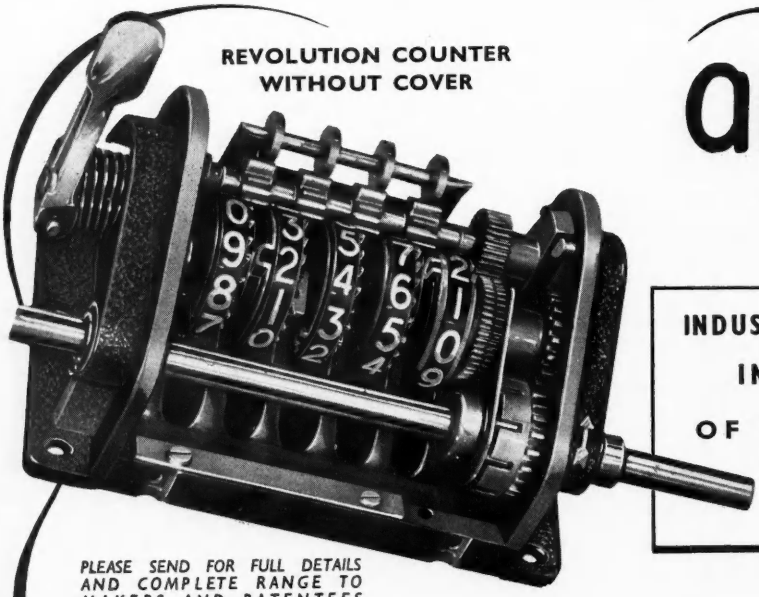

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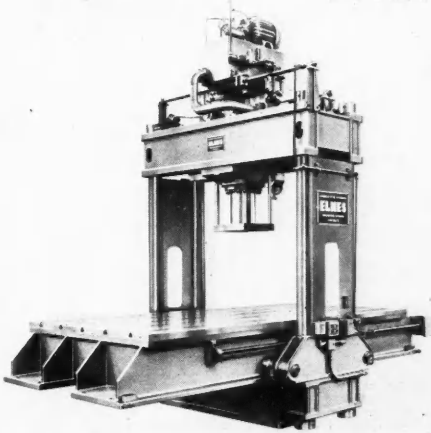
HYDRAULIC STRAIGHTENING PRESS

A new Elmes hydraulic straightening press, manufactured by American Steel Foundries, of Cincinnati, Ohio, and designed to meet the user's individual production requirements, has a capacity of 400 tons and a 24-in. stroke, and is equipped with a two-way travelling head.

The press, which is used for straightening large weldments and castings, consists of a massive one-piece bed weldment with removable bolster plate; a welded-steel bridge for supporting the travelling cylinders and power unit; two welded-steel side housings containing the four columns and steel rollers; and a welded-steel yoke, which passes under the bed and receives one end of each of the four columns. The columns are pre-stressed, holding the whole travelling unit in a rigid assembly. The total weight of the travelling unit is supported on four steel rollers running on tracks, one on each side of the press bed.

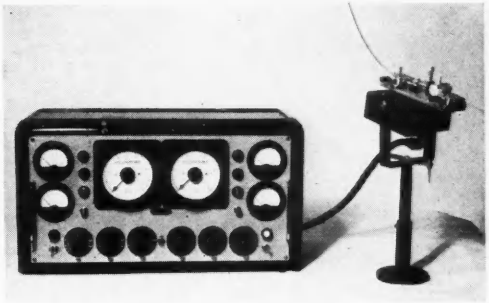


The ram is fitted with a guided platen, on which the straightening fixtures are mounted. Travel along the bed (a total of 144 in.) is provided by two lead screws, and movement of the pressure cylinder across the bed (a total of 60 in.) by one lead screw. Lead screws are controlled by reversing drum switches. A hand lever gives precise control over ram travel. Limit switches cut out the lead-screw drive motors when the limit of travel has been reached.

DIMENSIONAL LIMIT INDICATOR FOR ROLLED STRIP

Designed to give an instantaneous indication of any variation in the dimensions of metal strip during the final drawing process, the limit indicator manufactured by Sutton Coldfield Electrical Engineers, of Sutton Coldfield, Warwickshire, gives an immediate aural and visual warning of changes outside predetermined limits and, if required, can be made to stop the mill.

The control unit has duplicate indicators and setting controls for width and thickness measurement. The smaller meters show all dimensional variations (the upper positive, the lower negative), while the tolerance required can be preset by individual controls. Green



lights indicate whether the material is within the specified limits. Variations outside the tolerance limits are indicated by a red light (positive) or an amber light (negative), accompanied by a buzzer warning signal. A "break" contact is available to break the mill contactor circuit.

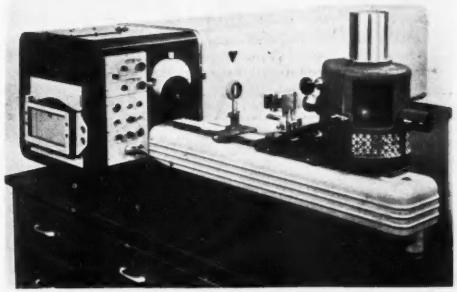
The micrometer unit, connected to the control unit by a flexible cable, is of small dimensions, for ease of fitting where there is little room between the die or rollers and the take-up drum. Ball-bearing guides accommodate the strip, and the assembly can be mounted to give an adequate float, where necessary, as the take-up drum fills. The essential electronic components are housed in a totally enclosed case with readily accessible adjusting controls.

The original unit was designed for inspecting strip approximately $\frac{3}{16}$ in. wide by 0·030 in. thick, but with suitable guides there is no limit to the dimensions of the strip which can be accommodated. Great sensitivity can be obtained with this equipment, and tolerance limits can be set within a range of $\pm$ 0·0003 to $\pm$ 0·01 in.

DUAL-GRATING SPECTROGRAPH

A new spectrograph, which achieves a high degree of speed and versatility through the use of two gratings, is announced by the Bausch & Lomb Optical Co., of Rochester, N.Y. Known as a dual-grating spectrograph, the instrument is designed to meet the increasing demands of spectrography, and, in addition to incorporating many innovations which give it greater flexibility and ease of operation, is stated to be the first of its kind to operate with two gratings, enabling it to photograph the complex spectra found in new metals and materials such as high-temperature alloys, uranium products, and rare earths.

The use of two gratings in the new spectrograph provides two different spectral ranges in a single exposure on a single plate or on two different plates, as follows:—One grating, with a range of 2000A (1st



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order), operates in a practical range of 1850 to 24,000A. The second grating, with a range of 1000A (1st order), operates in a range of 1850 to 12,000A. The spectra are recorded on a flat 4 × 10 in. plate or on two 2 × 10 in. plates.

Another feature of the unit is its " step-variable " slit. Previous slits (through which light from the specimen reaches the grating area) are of two types, i.e., fixed slits, which can be depended on to be the correct width but which are difficult to clean, and adjustable slits, which are easy to clean but which are not reliable as to width. The new " step-variable " system provides a slit which can be opened quickly for thorough cleaning but which is returned automatically to any one of several precise widths with an accuracy of 0·5 μ. Any one of several widths can be placed in operation with a simple dial-selection knob.

Many other design features of the new spectrograph have been developed to aid in producing more efficient analyses. Thus, dispersions are available from 8A/mm to 1·33A/mm; a fast optical system permits each grating to operate at f : 24; electrical controls are conveniently located and almost all are automatic; and the internal mechanism is completely protected against dust.

The extremely high actual resolution of the dual-grating spectrograph (over 160,000 in the second order) is stated to surpass the maximum resolution now available from the finest-grain spectrographic plates.

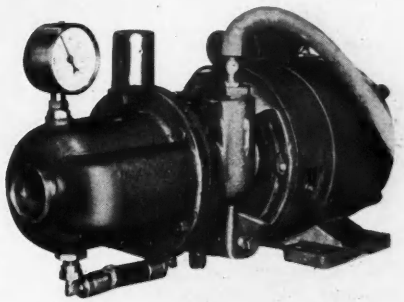
DIAPHRAGM AIR PUMP

Research into the problem of providing small quantities of compressed air at low pressures and completely free from oil vapour and other impurities has led The Hymatic Engineering Co. Ltd., of Redditch, Worcs., to introduce two versions of a new diaphragm-type compressor. Both providing a free air delivery of 2¼ cfm at 35 psi, the two models are designated DP2T and DP11, the DP2T (illustrated) having its own electric-motor flange mounted on the compressor body, and the DP11 arranged for belt drive from a separate power source. The equipment is designed for such duties as food processing, pumping consumable liquids such as milk, beer, vinegar, and soft drinks, pressurizing instruments, and for many special processes in medical or industrial laboratories.

Simplicity is a feature of the design. The conventional cylinder and piston are replaced by a multi-ply diaphragm, thus obviating any necessity for oil in the compression chamber. The connecting rod is an aluminium-alloy casting, shaped at the top into a circular disc, upon which the diaphragm is seated. At the top of the compression stroke, this disc conforms to the contour of the diaphragm, which has its outer edge nipped between the main casting and the compressor head. The plate holding the diaphragm in position on the disc houses the reed-type inlet valve, air thus being transferred through the diaphragm and its seating. The stainless-steel delivery valve of the same type is accommodated in the aluminium-alloy head sealing the compression space. This compression chamber is so designed as to help to damp out pulsation. The bottom end of the connecting rod is split, to house a sealed ball race constituting the big-end bearing. This, like the bearings of the hollow overhung crankshaft, is grease-packed, so that no servicing should be necessary between major overhauls.

SURGICAL SUCTION UNIT

A few years ago experiments were conducted, with the aid of the medical profession, on the use of a Mono pump as a suction unit to be employed in operating theatres. As a result, Mono Pumps Limited, of London, have now produced a small, compact unit which can be transported anywhere in the hospital, and which, furthermore, by virtue of its simple design, permits easy maintenance by any labour available in hospitals.



The fundamental principle of the Mono pump, with its single rotating element without valves, gearing, or lubricators, is ideal for the purpose. The unit is so constructed that any material accidentally aspirated into the pump will not damage the unit, with consequent loss of the normal vacuum (up to 28 in. Hg). The silent operation of this unit will not disturb the quiet essential for hospital work and it can be operated either in the theatre or in the ward. Two sizes are available, one suitable for operating theatres and the other for dental use.

POWER OSCILLATOR

The Model D120 power oscillator supplied by Goodmans Industries Limited, of Wembley, Middlesex, provides a power output of 120 W over a wide frequency range and has been designed for use with the Goodmans vibration generator, Model 390 A, where appreciable power is required for forced vibration excitation. The unit is a complete drive equipment, consisting of an oscillator and power amplifier, with its associated power supplies contained in a mobile console cabinet, the overall dimensions being 20 × 12 × 40 in. high.

The oscillator is a resistance-capacity, coupled, two-stage circuit employing automatic amplitude control by means of a thermistor in a feedback hoop. Tuning is effected by a continuously variable double potentiometer, in conjunction with a range switch selecting appropriate values of fixed capacity. Calibration adjustment is effected by preset potentiometers. All controls are grouped at a convenient height on the sloping control panel.

The drive to the amplifier is taken from a continuously variable potentiometer across the oscillator output, and this acts as a gain control. One half of a double triode valve operates as an amplifier and this feeds into the second half of the same valve, which operates as a

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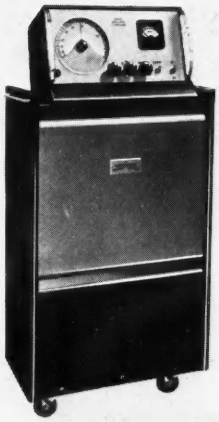


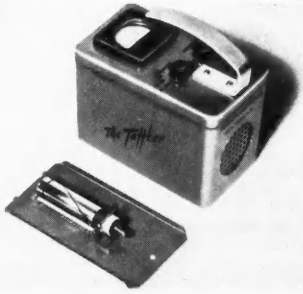
phase-splitter, driving a parallel push-pull output stage. Overall feedback is applied from the secondary of the output transformer to the cathode of the first amplifier stage. The main body of the console houses the power supplies and power amplifier, together with the special output transformer. Connections for the mains supply and the amplifier output are at the base of the rear panel, which can be removed to gain access to components and wiring. The valves and valve-current metering socket can be reached by removing the front panel on the main console. A thermocouple ammeter mounted on the control panel indicates the current fed to the moving coil of the vibration generator.

The frequency range is 10 to 10,000 cps in three ranges; calibration accuracy is $\pm 2\%$; and distortion is less than 2%. The power supply is a multi-tapped mains transformer for 100/120 V, 200/250 V, 50/60 cps, 700 VA.

GEIGER COUNTER FOR URANIUM PROSPECTING AND ASSAYING

A new type of Geiger counter for uranium prospecting and assaying, designated the "Tattler," is announced by the Radiac Company, Inc., of New York.

The new counter features a self-contained transistor-amplified loudspeaker, which can be regulated for pitch, enabling the user to dispense with earphones. Additional features of the "Tattler" include a removable base plate, permitting easy accessibility for Geiger-tube replacement, and an improved regulated high-voltage supply which maintains efficient operation throughout battery life. The Geiger tube can be replaced by either a single tube or an accessory cluster of six supersensitive bismuth Geiger tubes. Provision is made for plugging in a hand probe, or a deep-hole probe for drill-hole investigation.



The device has four ranges of sensitivity, appropriately calibrated for uranium prospecting in counts per minute. These four ranges, including a very sensitive "background" range, provide a broad intensity span, from low background to extremely "hot" intensity. The case is of scratch-resistant anodised aluminium. A convenient carrying handle permits easy transportation of the instrument, which weighs only 3 lb, and which was specifically designed for prospecting on foot and for deep drill-hole reconnaissance.

SMALL DUST-COLLECTING CYCLONE

In view of the importance of the problem of air pollution, many industrial users of solid fuel are turning their attention to the problem of dirt removal from the flue gases issuing from factory chimneys. To ensure that the plant is functioning satisfactorily, it is necessary to have some means of checking the cleaned gases; for this purpose, Nash and Thompson Ltd., of Tolworth, Surrey, have introduced the small dust-sampling cyclone illustrated.

By drawing a known amount of the flue gases through this cyclone, at an approximate rate of 20 cfm, it is possible to extract 95% of all solid matter down to a particle size of about 2 microns. This flue gas can be drawn through by means of a small blower or steam extractor, and the flow can be measured by means of a single orifice plate and inclined pressure gauge. The cyclone is of silvered-soldered construction and is lead-tin dipped to prevent corrosion by flue gases with a high sulphur content. A model in stainless steel is also available.

DRILL HOLDER AND SETTING GAUGE

A drill holder and setting gauge, designed to enable the accurate drilling of components to preset depths, is announced by B.S.A. Tools Ltd., of Birmingham. The holder can accommodate any size of drill, ream, counterbore, or tool possessing a standard morse taper shank. Its component parts are a main body, a knurled locking ring, and a combined bush and stop-nut.

To assemble, the drill is inserted into the holder, followed by the bush and stop-nut, which is threaded up the body an amount sufficient to give the required depth of drilling, i.e., the distance between the drill point and the lower face of the bush. The locking ring is tightened against the bush, once the required depth is determined. The complete unit is then inserted into the machine spindle.

An adjustable setting gauge is supplied with the unit, in order that the required depth of drilling can be readily and speedily checked. This gauge proves particularly useful after point-grinding the drill. The holder, bush and stop-nut, and locking ring are normally threaded left-hand. This is a precautionary measure against an inadvertent failure on the part of the operator to lock the bush in place. In such a circumstance, the bush would tend to work down the holder, where a normal right-hand rotation machine is employed, thus decreasing the drilling depth, to avoid excessive drilling.

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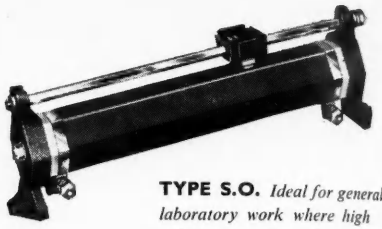

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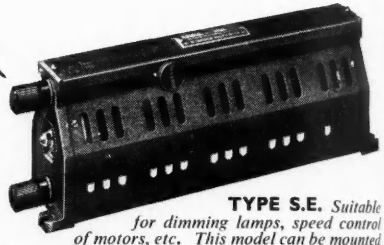

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PHYSICAL SOCIETY AND BRITISH INSTRUMENT INDUSTRIES EXHIBITIONS

The 1955 Physical Society Exhibition was held between April 25 and 28 at the New Hall, Royal Horticultural Society, Westminster. The British Instrument Industries Exhibition will be at Earls Court, London, from June 28 to July 9. In the following pages, details are given of some of the interesting instruments which have been or will be shown at these Exhibitions.

Amongst other items at the Physical Society Exhibition, including a double pulse generator and a wide-band oscilloscope, a new, high-grade general-purpose oscilloscope, type L.101, incorporating a dual-trace facility and featuring wide-band amplifiers, sweep expansion, and stabilized H.T. and E.H.T. supplies, has been exhibited by the Equipment Division of **Mullard Limited,** London. A tubular steel movable floor stand and an oscilloscope camera, as shown below, are available as accessories. This instrument should be of great value for the comparison and measurement of complex waveforms.

The dual-trace facility is provided on a conventional 5¼-in. tube by means of two identical Y amplifiers and an electronic switch. Each amplifier is switched through to the cathode-ray tube on alternate sweeps, the electronic switch being operated during flyback. There is no interaction between the channels, each of which has a frequency response from 10 cps (1 db down) to 4 Mc/s (3 db down). The rise time of the amplifiers is 0·1 microsecond. Identical attenuators, embodying close-tolerance high-stability components, are provided for each channel, and permit the sensitivity to be adjusted from 0·02 V peak-peak/centimetre to 100 V peak-peak/centimetre in twelve steps. The frequency response of the amplifier channels remains constant for all attenuator settings. Voltages can be measured within 5%. The dual-trace facility can be switched out when not required.

The Miller time base can be free-running, synchronized, or triggered. Sweep velocity is variable between 10 cm/microsecond and 0·1 cm/millisecond. The sweep length may be expanded in three switched steps to 10 cm, 20 cm, and 50 cm. Velocity adjustments have negligible effect on sweep length. Time can be measured with an accuracy of ±10%. The time-base output stage can also be used as an X amplifier, with a sensitivity of 0·7 V/cm and a band width of from 2 cps to 300 kc/s.

The oscilloscope is self-contained in an aluminium-alloy cabinet (height 14 in., width 10½ in., depth 27 in., weight 60 lb). The power unit is located at the rear of the case and is shielded from the tube. This unit is easily removable for maintenance, connections to the rest of the oscilloscope being by plug and socket. Amplifiers and time-base units are easily accessible. High-quality components are employed throughout, and there are no electrolytic capacitors. The oscilloscope is suitable for semi-tropical use.

A wide selection from their ranges of ammeters, voltmeters, frequency indicators, power-factor indicators, and synchroscopes will be shown by **Crompton Parkinson Ltd.,** at the B.I.I. Exhibition. Several of these instruments have been recently introduced.

Of particular interest will be Admiralty-pattern shock-proof instruments, those to be displayed including the new power-factor indicators and synchroscopes. These instruments have been built to withstand exceptionally arduous service conditions and were accepted by the Admiralty after the satisfactory conclusion of a comprehensive series of shock and vibration tests, etc.

Also of special interest will be the newly introduced hermetically sealed circular-scale instruments. These instruments have been built to withstand a temperature range of −40° F up to + 158° F under conditions of 95% humidity and to sustain without leakage an internal pressure differential of 10 psi. They are guaranteed, moreover, to be shock-resisting up to 50 *g*.

Other instrument exhibits of interest include switchboard-mounting 4-in. and 6-in. dial types with either short scales or circular scales in pressed steel cases and for projecting or flush mounting; portable instruments, including the new circular-scale designs; ammeters and voltmeters for mining, industrial, and marine controller mounting; and sector-pattern ammeters, voltmeters, and frequency indicators.

The "Pegasus" Packaged Computer No. 1, shown at the Physical Society Exhibition by **Ferranti Ltd.,** of Hollinwood, Lancs., is a new, medium-sized, general-purpose digital computer, suitable for a wide variety of calculations arising in industry and scientific research. In this computer (illustrated overleaf), emphasis has been laid on providing facilities which simplify the preparation of a calculation.

The "Pegasus" is built from standardized plug-in units, for ease of maintenance and replacement. Computation takes place in an immediate-access store of 43 single-word registers, consisting of nickel delay-lines. This is backed up by a magnetic-drum store with a capacity of 4096 words.

In addition to X-ray rubes and equipment, miniature spectral light sources, stroboscopic sources, high-speed tape readers, and viscometers, other Ferranti exhibits include afterglow measurement gear, designed to determine the decay curve of luminescence of a cathode-ray-tube phosphor as a function of time, and a demonstration model of a precision position locator. This interesting exhibit demonstrates the application of electronics to provide the solution to a well-known problem in mechanical engineering, namely the accurate

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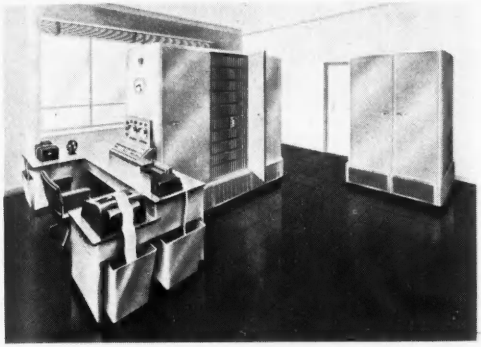
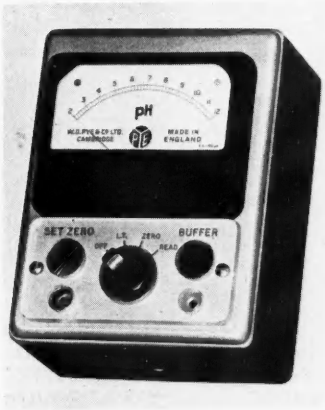


positioning of one object relative to another. The method of measurement makes use of prismatic gratings consisting of glass strips carrying a line structure. A beam of parallel light is passed through two of these gratings superimposed, and the movement of one grating with respect to the other produces a modulated light pattern which varies through one complete cycle of light and darkness for a relative movement of one line width.

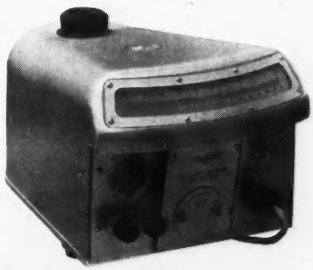
In applying this principle to the measurement of movement of a body, such as the table of a machine tool, a long grating is attached to the body and two narrow beams of light are passed through this grating and through a small stationary grating, two beams being used so that the direction of travel can be ascertained. Each beam is collected and passed to a separate photo-electric cell, which gives an electrical signal output every time the light is unobscured by the presence of lines. These signals are counted as the table moves and give an exact measurement of the distance travelled. The accuracy of measurement is governed by the number of lines and, in the case of a grating having 5000 lines per inch, control to 0·0001 in. is possible.

The miniature pH meter shown at the Physical Society Exhibition by **W. G. Pye & Co. Ltd.,** of Cambridge, has been designed to satisfy the need for a pH meter which is portable and independent of mains supplies. Among the tests which may be performed with advantage by the use of this instrument are those connected with plating solutions, dye liquors, works effluents, domestic and industrial water supplies, the manufacture of insecticides and fertilizers, and the measurement of soil pH. Its accuracy is such that it can be used for most laboratory measurements, particularly where simplicity of operation and low price are important.



The circuit of the instrument comprises a four-valve amplifier with a large degree of negative feedback, giving exceptional linearity and accuracy. The valves are robust sub-miniature types with a very low power consumption, thus contributing to extended battery life, which is normally greater than 250 hours of continuous use. The input valve is of the electrometer type, permitting the use of robust (high-resistance) glass electrodes. A manual temperature compensator is fitted, and this is accessible from the back of the case; this compartment also houses the battery-checking controls.

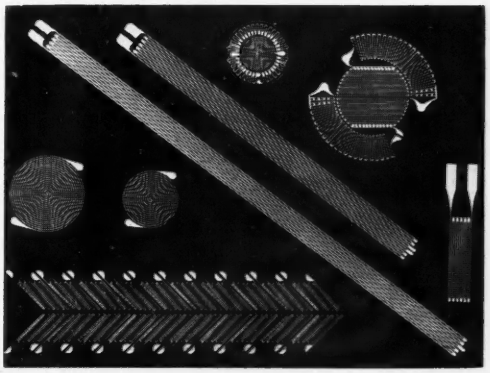
Another interesting instrument among the many exhibited by Pye is the prototype (illustrated below) of a voltmeter with a resistance of 1 megohm per volt, this high value being obtained by the use of a suspended galvanometer.



Designated the "Scalamp" Megohm Voltmeter, this instrument can be used for measuring low voltages, and has ranges as low as 10 mV for full-scale deflection. The scale is approximately 5½ in. in length, and the light spot has a hairline which permits readings to be taken with very high accuracy. There are 10 ranges, from 10 mV to 300 V, and the specified accuracy is ± 1% of full-scale deflection. The instrument is robust and simple to use, and provision is made for shorting the coil automatically when the instrument is turned off and when it is lifted from the bench.

Among other equipment shown at the Physical Society Exhibition by the Electronics Division of **Saunders-Roe Limited,** of Osborne, East Cowes, Isle of Wight, was a range of foil strain gauges, as illustrated below. These gauges are made from thin metal foil mounted on an ethoxylene lacquer backing, and the foil may be etched into any two-dimensional pattern.

The outstanding advantage of this method of strain-gauge manufacture is that, because of the rectangular cross-section of the elements, very high input currents may be used with stability. It is therefore possible to operate robust meters and recording galvanometers directly, thereby simplifying instrumentation.



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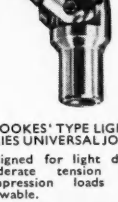

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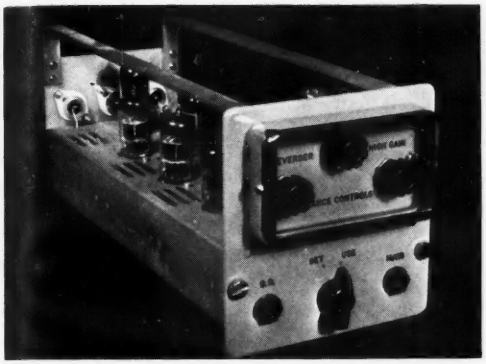
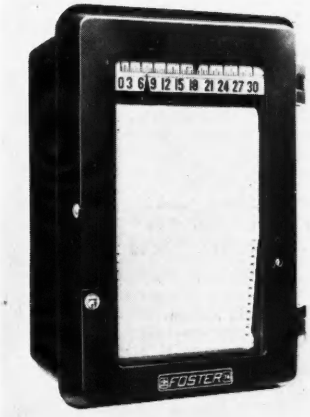


Other items exhibited include a static strain bridge, a displacement meter, an electronic multiplier, a "Miniputer," which is a small table-top analogue capable of solving linear simultaneous differential equations where time is the independent variable, and a computer amplifier (illustrated above).

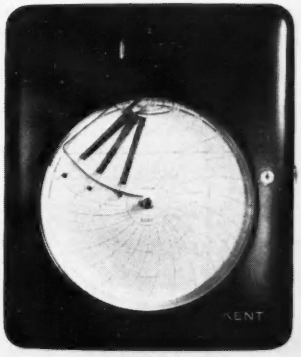
This amplifier has been designed for use in high-accuracy, slow-speed, d.c. analogue computers or for high-speed repetitive computing, and consists of a high-gain drift-corrected amplifier and a drift-compensated, unity-gain amplifier as a sign reverser. The main amplifier will perform the operation of summation, integration, and differentiation, and will provide any desired transfer function, when used in conjunction with suitable computing impedances.

In addition to a wide range of temperature-measuring instruments, including resistance, optical, and radiation pyrometers, **Foster Instrument Co. Ltd.,** of Letchworth, Herts., will be showing at the B.I.I. Exhibition a range of introscopes for the inspection of normally inaccessible surfaces, including one model which uses a new method of inspecting surface finish in the bore of small holes from $\frac{1}{8}$ in. diameter upwards. Another exhibit will comprise smoke-density detecting, indicating, and alarm equipment, functioning on the principle of interference by smoke of a constant-intensity light source focused onto a photoelectric cell.

The latest type of Foster electronic continuous-balance potentiometric indicators and recorders will also be shown. These instruments have been designed to cover a wider field of application in research and industry than is possible with the millivoltmeter type of instrument, and can be fitted with various forms of control contacts for automatic temperature control. One of the most important features is the use of a constant-voltage mains unit, which provides the current for the slide-wire circuit. This unit gives a low-voltage d.c. output constant within $\pm$ 0·25% for variations up to 10% in the mains voltage. The elimination of the dry cell or other source of supply makes periodic manual or automatic standardization unnecessary. An electronic continuous-balance strip-chart indicator recorder is shown in the illustration.



A number of new industrial measuring and controlling instruments in their "Commander" class will be shown for the first time at the B.I.I. Exhibition by **George Kent Ltd.,** of Luton, Beds. These instruments, in which case design and many internal parts have been standardized to B.S. specifications—an obvious advantage—will include applications for the recording, indicating, integrating, and controlling of flow, pressure, level, temperature, and other variables, all with standardized "presentation." In addition, instruments with a number of combinations will be on view, as well as specialized instruments, such as boiler test indicators and receiver recorders, all of the "Commander" class. Associated with this range of "Commander" instruments will be a display showing the extent of interchangeability possible with these new instruments, an example of which (for recording three pressures simultaneously) is illustrated below.



Examples of Kent equipment in various industries will also be exhibited. Thus, for instance, for the gas industry, there will be a presentation of the much-discussed Wobbe-index control, instruments and controllers for gas grid control, and a new diaphragm-operated gas-pressure controller, as well as oxygen analysers and manometers. In the glass-industry section, feeder-glass temperature control will be the main feature, as well as a working demonstration of the automatic control of glass "metal" level for glass-melting tanks.

The widely used Kent systems for the automatic control of furnace temperature and combustion for various applications in the steel industry will also be exhibited, in the form of a 5-section unit panel for soaking-pit control. Other items in this section comprise pneumatic computers, bleed units, injector units, and power cylinders for automatic regulation.

The water-industry section will include a working display of the Universal glass-electrode pH recorder, a model of the new Dall tube, and another working exhibit with a "Commander"-class electrical flow transmitter working from an orifice fitting in a water supply and telemetering to a set of standard receiving instruments on a panel. A wide range of Kent mechanical water meters, including the new "Master range," will also be on view.

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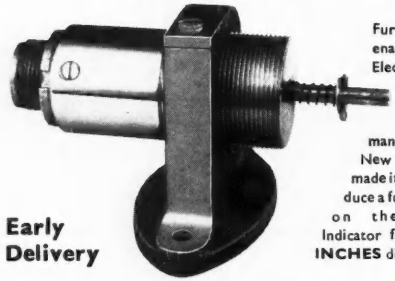

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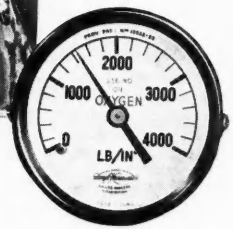

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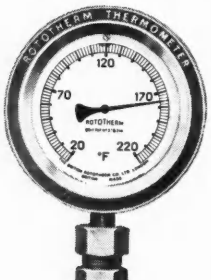

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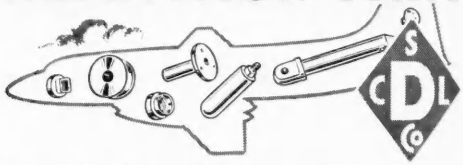

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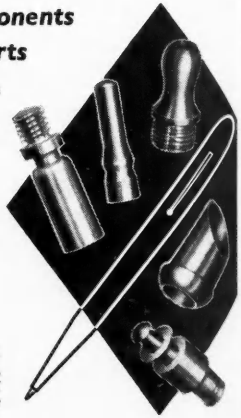

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An actual trade-effluent control scheme will be displayed in the sewage section, including a flow recorder and pH controller actuating a power-cylinder-operated lime-dosing trough. In the chemical-industry section, two industrial applications of importance to chemical engineers will be shown, i.e., a presentation of the instrumentation of a sulphur recovery plant, and a working installation of " simmering " control. Rotary-shunt steam meters will also be exhibited here.

For the sugar industry there will be a complete presentation of the instrumentation of a diffusion battery, while the oil-industry section will contain a full range of Brodie-Kent meters, a demonstration of an oxygen controller, working in conjunction with a gas-fired heater, and a working model showing the comparison between the Dall tube, the Venturi tube, and orifice fittings as differential producers for flow measurement.

Standardization of instrumentation and control for industrial boiler plants will be the main feature of the steam-power section, where a set of sectional panels will demonstrate this new trend. Additional features will be a demonstration of a combined turbine and boiler control panel and console, and a display covering the automatic control of the temperature of superheated steam.

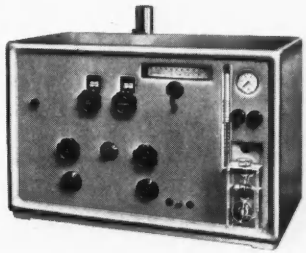
The latest development in the electromagnetic transducer system were featured by **Salford Electrical Instruments Ltd.** at the Physical Society Exhibition. Basically, this system provides for the electrical remote indication of very small mechanical displacements. Two units only are employed, any movement of a stylus incorporated in an electromagnetic measuring head causing a variation in the magnetic flux, which is transmitted directly to a moving-coil measuring instrument of the dynamometer type. No thermionic valves, barretters, or magnetic amplifiers are used, and the system is independent of voltage changes.

The range of the transducer system has recently, however, been greatly extended by the introduction of various pressure-responsive elements such as diaphragms, capsules, or bourdon tubes, which can be used in conjunction with the electromagnetic measuring head. The new equipment now enables the pressures at widely scattered or inaccessible and dangerous points to be measured at a central control station, situated in a safer location. Similarly, the pressure in a movable device can be measured in a fixed control station. Absolute, direct, and differential pressures can all be measured by this apparatus. The transducer system has also been adapted in the same way for the measurement of load, thrust, and torque.

Salford Electrical Instruments Ltd. have also introduced a new G.E.C. range of laboratory standard instruments at this Exhibition. These are available with two types of movement, i.e., moving coil for the measurement of d.c. voltages and currents, and dynamometer single-element for the measurement of both a.c. and d.c. voltages, currents, and power. The new instruments, which are of precision accuracy, are internally screened and are fitted with a spirit level, a thermometer, and levelling feet. The scales have a mirror inset, are vernier-calibrated, and are 12 in. in length.

The requirements of a versatile flame photometer with high performance characteristics are a stable flame intensity, a simple and reliable atomizer and sample-handling system, and a stable detecting and measuring system. These requirements are fulfilled in the new flame photometer exhibited at the Physical Society Exhibition by **Unicam Instruments Ltd.**, of Cambridge.

In this instrument, an air supply at 24 psi operates a concentric-jet atomizer, which feeds a burner using either propane or acetylene, depending on the flame temperature required. Pressure gauges and controls are located in the atomizer compartment, with funnel feed to the atomizer mounted on the front panel. Parts of the apparatus in contact with the sample are of glass. Light from the burner passes into a monochromator of high light-gathering power, based on the compensated spherical-mirror design described by Czerny. A fused silica prism is used which, in conjunction with a photomultiplier and a lead sulphide cell, is suitable for measurements from 250 mμ to 2·7 μ. Wavelength selection is made by varying the angle of the Littrow mirror. Other controls include slit-width, dark-current, and sensitivity controls. Radiation leaving the exit slit is chopped at 100 cps and focused by a concave



mirror to the selected detector. The use of chopped radiation ensures good zero stability. A homodyne rectifier (with phasing pulses taken from the chopper disc) converts the a.c. output to a d.c. signal. Readings are taken directly from a spot galvanometer, which may be connected to a recorder, if required.

Other instruments to be shown by Unicam at the B.I.I. Exhibition include a new infrared spectrometer, ultraviolet and visible spectrophotometers, and crystallographic equipment.

The Heat Processing of Combustible Material

(*Concluded from page* 193)

have practically revolutionized this branch of the printing industry.

Dual Burner

One development of particular importance in the flame-impingement and high-temperature radiant-heat processing of combustible materials is a dual-type burner which combines the features of the pressurized multi-ported ribbon burner and the high-temperature radiant burner.

This burner is constructed in the form of an inverted V. The gaseous fuel is fed under pressure to the manifold at the top, and a ribbon flame burns downwards from the apex of the inverted V and the cavity immediately beneath it. The high-intensity flame burns along the sides of the V, causing these " cheeks " to become radiant.

This burner, mounted on a special frame and mechanism designed to move a travelling web of cloth into and out of the V of the burner, constitutes a modern singeing machine. It has enabled the textile industry to quadruple its former rate of production of singed cloth, without any increase in required floor space, and at a greatly reduced saving in labour-handling costs. Equally important is the fact that this combination of flame and radiant heat produces a singed product of a superior quality not matched by methods formerly used.

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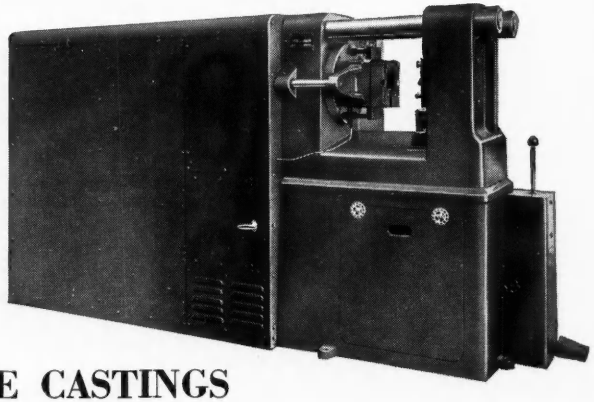

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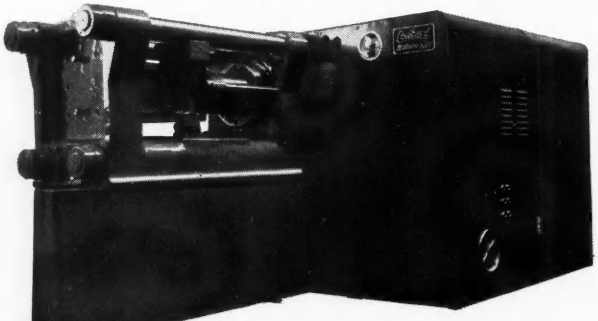

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The History and Development of Aluminium and its Alloys

By Dr. Ing. A. von Zeerleder.*

Despite the fact that aluminium is the most abundant metal in the earth's crust, its content being about 7·5%, it was not until 1805 that it was first discovered in England by Davy (Fig. 1†), and prepared in 1825 by the Danish scientist Oersted, who reduced aluminium chloride by potassium amalgam. In 1827, Wöhler in Germany improved on this method and determined the physical properties of the new element.

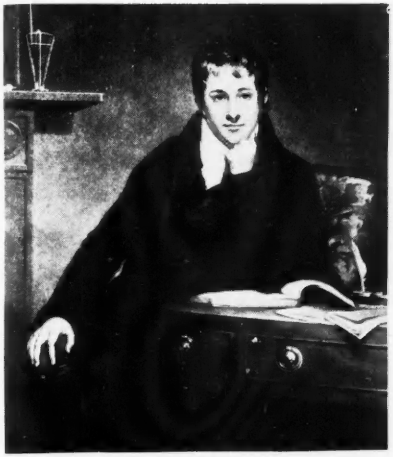

Fig. 1. **Sir Humphry Davy (1778-1829), who discovered aluminium in 1805, first called it "Alumium" and subsequently "Aluminum," but never "Aluminium." Presumably, Davy and 150 million Americans can't be wrong.**

An industrial process for the preparation of aluminium was devised in 1854 by Sainte-Claire Deville (Fig. 2†), who substituted stable sodium-aluminium-chloride for the highly hygroscopic aluminium chloride and sodium for the more expensive potassium. The price of a 60-lb batch of aluminium prepared in 1856 by Deville amounted to about £20 per lb. By 1880, when the price dropped to about 28 shillings per lb, aluminium was still more expensive than silver. It was only with the invention by Héroult and Hall of the electrolytic process for the preparation of aluminium that its price dropped to the level of other industrially important metals.

Both Wöhler and Sainte-Claire Deville were already aware in 1854 of the possibility of preparing aluminium by electrolytic reduction of its oxide. As, however, a cheap source of electric power had not yet been invented, no industrial application was at that time possible. In 1886, when cheap electric power was a reality, Héroult in France and Hall in America were able to develop the industrial electrolytic process. Since then aluminium is exclusively prepared by this process, which consists of a reduction of alumina (Al_2O_3), dissolved at 950° C in cryolite ($AlF_3.3NaF$). In Europe this process was first used and industrially developed by Aluminium-Industrie Aktien-Gesellschaft (A.I.A.G.), Neuhausen; in the U.S.A., Hall erected the first plant for the Pittsburgh Reduction Company at Pittsburgh.

This process made possible the preparation of aluminium at an industrially attractive price. It is surprising with what far-sightedness Sainte-Claire Deville recognized a century ago the development possibilities of aluminium. In his report on the London Exhibition of 1862, at which aluminium was first exhibited, he wrote:—". . . Aluminium is the intermediate metal between the precious and the common metals. This intermediate link was lacking and was replaced by rather poor alloys. . . . Aluminium has, therefore, its proper place in technique, because of its acoustic properties, its malleability, its ductility, and its low density. . . . If, however, means are eventually found to prepare aluminium from alumina, its ore, . . . aluminium will be one of the most common metals. . . ."

Among the advantages of aluminium are its casting properties, its malleability, its good thermal and electrical conductivity, its good corrosion resistance, and its low density. Its mechanical strength and machinability are, however, relatively poor; this is true for any pure metal. The chief applications of pure aluminium have therefore been for electrical transmissions (mainly overhead), for the chemical and food industries, for kitchen-ware (Fig. 3†), for storage containers, and for packaging. Special and very interesting applications have been developed for aluminium foil.

Casting Alloys

Up to the turn of the century, development was mainly confined to casting alloys, while for rolling and extruding pure aluminium was mainly used.

The earliest castings were made from metal of commercial purity, possibly with accidental admixtures of small proportions of other metals cast in the same foundry. In Great Britain, Gilbert's "Eros" in Piccadilly Circus is the best-known example, and samples from this statue have shown the metal to be of low purity, with a rather high copper content in some of the cast components. A still earlier statue, in the possession of the Aluminium Development Association, London, is a small reproduction in aluminium of the Diana de Gabies (Fig. 4†), which is believed to have been cast in about 1860 in metal produced chemically by Deville.

Fig. 2. **Henri Etienne Sainte-Claire Deville (1818-1881), who may be called the father of aluminium as an industrial metal, not only devised an industrial process for its manufacture but showed remarkable foresight in recognizing the possible advantages of aluminium alloys.**

* Professor at the Eidg. Technischen Hochschule, Zurich; Director of the Research Institute of A.I.A.G., Neuhausen.

† None of the illustrations in this article or their captions were supplied by the author. Editor E.D.

Fig. 3. **Aluminium cooking equipment designed for the Major F. G. Jackson-Harmsworth Polar Expedition of 1894/1897.**

Analysis in 1953 showed the aluminium to contain 2% copper and 1% silicon.

The first navigable Zeppelin airship, built in 1900, was provided with a structure made of pure aluminium sections, though Sainte-Claire Deville had already in 1859 in his book "L'Aluminium" pointed out the interesting properties of aluminium alloys. In the field of transport, advantage has long been taken of aluminium (Figs. 5 to 8).

Insofar as aluminium casting alloys are concerned, the German alloy with 3% copper and 10% zinc, and the American alloy with 7 to 9% copper, were the first to have any large application, though they are no longer used nowadays. During World War I, Rosenhain developed at the National Physical Laboratory at Teddington an alloy—the famous Y-Alloy—containing 4% Cu, 2% Ni, and 1·5% Mg. Y-Alloy is age-hardenable and, owing to its high heat strength, is specially suitable for pistons for aviation engines and cylinder heads. This was the first age-hardenable casting alloy.

At the same time, an American, Adalar Pac, produced a eutectic aluminium-silicon alloy. According to Pac's process, about 0·1% of a special sodium salt mixture was stirred in the alloy, which afterwards solidified eutectically. Up to that time, silicon had been looked upon as a detrimental addition to aluminium, though Sainte-Claire Deville had in his above-mentioned book pointed out the favourable properties of aluminium-silicon alloys. This eutectic alloy is outstanding in castability; its mechanical strength is, however, rather poor, as also is its machinability. By further additions, such as copper and especially magnesium, the alloy becomes age-hardenable; workability and strength are thereby greatly improved.

Fig. 4. **Though not as famous as Gilbert's "Eros" in Piccadilly Circus, this reproduction in aluminium of the Diana de Gabies in the Louvre is considerably older, and is believed to have been cast in 1860 in metal produced chemically by Sainte-Claire Deville.**

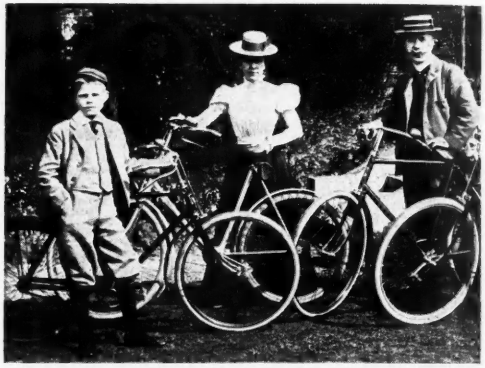

Fig. 5. **The aluminium bicycle in the centre of this illustration was built before 1897 and incorporated such ultra-modern refinements as a pneumatic saddle (inflated by a pump) and pneumatic brakes, air pressure for which was built up by a hand-operated rubber bulb.**

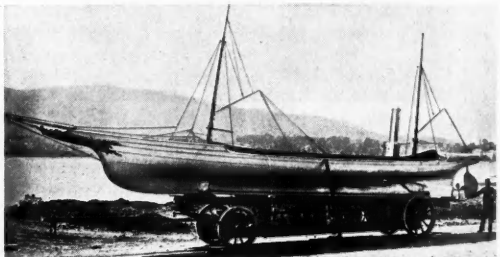

Fig. 6. **The "Mignon," 1892. This Swiss steam launch is believed to be one of the earliest examples of the use of aluminium in shipbuilding.**

Fig. 7. **This 1902-model Panhard embodied numerous aluminium components, including the crankcase, with integral engine front mounting brackets, the oil sump, the gear box, the differential casing, the timing-chain casing, the driving pulley for the oil pump, the oil-pump box cover, the ignition-switch box cover, body panelling, and the bonnet (not shown).**

At the turn of the century, Mach in Germany had by chance discovered the advantageous properties of aluminium-magnesium alloys. The Magnalium Company in Germany undertook the industrial development of these alloys. Unfortunately, the corrosion resistance of the magnesium at that time available was so poor that these alloys did not prove successful. Some time later, Griesheim Elektron succeeded in the development of an aluminium-magnesium alloy with 4-12% magnesium. Compared with aluminium-silicon alloys, these alloys have a lower specific gravity and are outstanding in their resistance to sea-water corrosion.

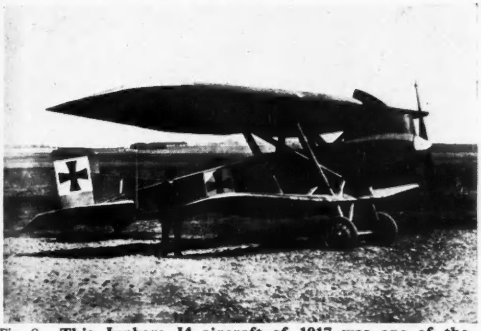

Fig. 8. **This Junkers J4 aircraft of 1917 was one of the earliest aircraft to use an aluminium alloy in its wings and fuselage, its interplane struts, and its undercarriage.**

In addition to the age-hardenable aluminium casting alloys with high silicon contents, A.I.A.G. has developed an Al-Si-Mg alloy with a low silicon content, called "Anticorodal." Special importance attaches to the Al-Zn-Mg alloy "Unifont," which was developed by the same Company and which contains 1% magnesium and 5% zinc. A special feature of this alloy is that it age-hardens at room temperature without any solution heat treatment and quenching. Its mechanical properties are, however, lower than the corresponding properties of the aluminium-silicon casting alloys. A new group of age-hardenable aluminium casting alloys has been developed, again by Pac, on the basis of 4·5% copper and 0·3% titanium. These alloys show especially good toughness and ductility.

Apart from age-hardenable casting alloys prepared from virgin metal, alloys prepared from scrap metal are used to an increasing extent. These are less costly and have therefore gained wide application.

WROUGHT ALLOYS

Development of wrought alloys has taken place almost completely within the present century. The alloy "Magnalium," already mentioned under casting alloys, has also been used for sheets and sections, but again with little success, owing to its low corrosion resistance.

The decisive event leading to the introduction of aluminium alloys for sheets and sections was the invention of duralumin by Wilm in 1906; duralumin is an Al-Cu-Mg-Mn alloy which age-hardens when solution-heat-treated and quenched. Wilm had been given the task of developing an alloy for cartridges for the Nobel Dynamite Group. He did not succeed in solving this problem and his employers at first paid very little attention to the invention of duralumin, to a certain extent a by-product of this work. They even refused to meet the costs of the patent application. Three years later, in 1909, Wilm applied personally for the basic patent for the age-hardenable Al-Cu-Mg alloy. This invention paved the way to the enormous development of aluminium alloys which from then on found their way into practically all lines of technique (Fig. 9).

The solubility of copper in aluminium decreases considerably with decrease in temperature. At 548° C the solubility of copper is at its maximum with 5·7%, while at room temperature it is as low as 0·3%. The age-hardening of aluminium-alloys is based on this phenomenon. Similar age-hardening effects have since been found and technically developed with other metals.

With a yield point of 28 kg/mm², a rupture strength of 40 kg/mm², and an elongation of 20%, this duralumin alloy, which in Switzerland is known as "Avional," corresponds to normal mild steel, while its specific gravity is 2·8, or only one-third that of iron.

Mention must also be made of the Y-Alloy developed by Rosenhain, and already described under casting alloys. While duralumin reaches its maximum mechanical strength after ageing for 4 days at room temperature after quenching, Y-Alloy must be aged artificially at temperatures between 100 to 200° C. As a rule, it is quenched and then aged for 8 hours at 150° C; by means of this treatment it attains a yield point of 21 kg/mm², an ultimate strength of 37 kg/mm², and an elongation of 17%.

At the same time, Giulini (1918) discovered the copper-free Al-Mg-Si-alloys which, like Y-Alloy, are artificially aged. The chief representative of this type is "Anticorodal," which was developed by A.I.A.G. Anticorodal, age-hardened to its maximum, shows a somewhat higher yield point than duralumin, while its rupture strength and elongation are slightly lower.

The rapid development of engineering technology made alloys of higher strength than duralumin desirable. From 1930 onwards, intensive systematic work was started to create new high-strength alloys, partly on the principle of the duralumin type, and partly along quite new lines. Of these, super-duralumin goes back to 1932, when Messner at Düren attained with this alloy a yield point of 34 kg/mm² and a rupture strength of 47 kg/mm². This aluminium-copper-magnesium alloy is also age-hardenable, the precipitation of alloy components being increased, compared with duralumin, and its corrosion resistance considerably reduced.

Fig. 9. **The "Graf Zeppelin" in flight over Buenos Aires, 1934. Duralumin was extensively used in its construction**

In order to improve the corrosion resistance of these heat-treated alloys, sheets are plated with pure aluminium or a corrosion-resistant alloy. If an artificially age-hardenable alloy like Anticorodal is used for this purpose, the cladding hardens together with the core, when solution-treated and quenched. The thickness of the cladding amounts to 10% on each side for thinner sheets and decreases to 5% for thicker sheets.

All age-hardened alloys have the disadvantage that, when heated above 100° C, they lose strength. For this reason age-hardened alloys are as a rule not joined by welding or brazing and, after age-hardening, no forming operation necessitating heat may be applied. To overcome this disadvantage, the Al-Mg alloys were reintroduced from 1931. Magnesium is now available in high purity and therefore corrosion-resistant alloys can be produced.

With increasing magnesium content the yield point and rupture strength of these "Peraluman" alloys increase. For magnesium contents above 4·5%, the increase in yield point is small. On the other hand, alloys with higher magnesium contents are subject to stress corrosion; to overcome this tendency, a special heat treatment must be used. Furthermore, workability decreases with increasing magnesium content, and alloys with 9% or more magnesium are now hardly in use. For marine purposes the very good corrosion resistance against sea-water of the 4·5% Mg alloy is a special asset.

Since 1936, a further alloy group has been developed, with very high mechanical properties. These alloys are composed of aluminium, zinc, magnesium, and copper, and contain minor corrosion-inhibiting additions of manganese and chromium. The first alloy of this type was developed in Japan under the designation "Thom." This alloy must, however, have had a rather low corrosion resistance. It took ten years of world-wide research on this alloy system before a practical and reliable high-strength alloy of this type was produced. The corrosion resistance of the alloy may be improved by plating with an aluminium alloy of lower zinc content. The strength is thereby somewhat decreased. This alloy also must be age-hardened; the solution-treatment temperature of 465° C is, however, 40° C lower than for the "Avional" alloy.

Fig. 10. **Latest model of London Transport omnibus. In this 1954 L.T.E. "Routemaster," designed to carry 64 seated passengers, aluminium alloys are used for many components, including the under-frame, body pillars and sides, floor bearers, and upper roof structure.**

A.I.A.G. has developed a zinc-magnesium wrought alloy, known as "Unidal," which age-hardens by itself after hot and cold rolling and attains medium mechanical properties. This alloy may, like Al-Mg alloys, be welded and afterwards regains its normal strength.

A new development has been initiated by the Research Laboratories of A.I.A.G., leading to S.A.P. (sintered aluminium powder). Irmann found by chance that pure aluminium powder, with an oxide content of 10 to 15%, can be sintered and extruded to a material of exceedingly high strength properties. A special feature of this material is that it does not soften, even when heated for very long periods to temperatures just below its melting point (657° C). Strength at normal temperature is regained and above 250° C it is stronger than all known aluminium alloys. This S.A.P. opens up new and interesting applications for aluminium in the temperature range between 250 and 550° C, a range from which aluminium had previously been excluded, owing to its unsatisfactory properties.

Fig. 11. **Office building for the Aluminum Company of America. This 30-storey building features reversible aluminium windows, aluminium curtain walls, aluminium wiring, and aluminium radiant-heating ceilings.**

At the moment, it is hardly possible to forecast definitely future trends in the development of aluminium alloys. The steady improvement in their properties, insofar as strength, corrosion resistance, and workability are concerned, will certainly continue, and, to-day, aluminium alloys are extensively used in extremely wide fields of applications, ranging from saucepans to sewing-machines, and from buses to buildings (Figs. 10 and 11).

The fear that over-production of aluminium would be the result of the decrease in armament requirements after World War II has not been justified. On the contrary, despite increased production, there is still a pronounced shortage of aluminium. Indeed, the increasing demand for this valuable engineering material indicates that considerably higher production is inevitable.

Acknowledgements:—
Figs. 1 and 2:—The Royal Institution, London.
Fig. 3:—The Scott Polar Research Institute, and the Aluminium Development Association, London.
Fig. 4:—The Aluminium Development Association, London.
Fig. 5:—W. A. Woodward, Esq.
Fig. 6:—A.I.A.G., Neuhausen, Switzerland.
Fig. 7:—R. K. S. Clarkson, Esq.
Fig. 8:—The Aluminium Development Association, London.
Fig. 9:—C. V. Lezard, Esq.
Fig. 10:—London Transport Executive.
Fig. 11:—The Aluminum Company of America.

British Standards for Aluminium

By E. Elliott, A.Met., A.I.M.*

A STANDARD for any material is a yardstick to which the producer must conform and by which the consumer is assured of a certain minimum degree of quality.

The first specifications for aluminium and its alloys were undoubtedly purchasing documents, i.e., written conditions and requirements imposed by individual users upon suppliers. Such individual specifications are highly undesirable, resulting as they inevitably do in a multiplicity of alloys, each tailored to very narrow fields of application. Happily, they are now rare, as far as aluminium is concerned, having been replaced by the nationally produced standards of an independent body, the British Standards Institution. The B.S.I. traces its history back to 1901, when it was founded as the Engineering Standards Committee of the Institution of Civil Engineers, Mechanical Engineers, and Naval Architects, and to the Iron & Steel Institute, which became the British Engineering Standards Association in 1918, and assumed its present title in 1931, a Royal Charter having been granted in 1929.

The B.S.I. produces standards for aluminium and its alloys for general engineering purposes, and also for the specialised field of aircraft construction, where obviously more stringent requirements are essential. For aircraft alloys of recent development, specifications are issued by the Directorate of Technical Development of the Ministry of Supply, the well known DTD specifications, which are regarded as provisional. This provides a mechanism for the use of improved materials during a period when they must still be regarded as undergoing development.

Standards for Aluminium-Alloy Ingots and Castings

The first comprehensive standard for aluminium-alloy ingots and castings was published in 1949, namely BS. 1490 "Aluminium and Aluminium Alloy Ingots and Castings for General Engineering Purposes." This is one of a series of standards, those for the wrought forms being discussed later. It covers, in addition to pure aluminium ingots, twenty alloys in the form of ingots and castings and, in its specific clauses, defines limits of chemical composition and minimum mechanical properties to be obtained on separately cast test bars in the as-cast and, where applicable, heat-treated conditions. The mechanical properties specified are the tensile strength and elongation, with hardness values for certain piston alloys. General clauses cover the methods and condition of testing, referee tests, freedom from defects, pressure tightness and inspection, and tolerances on dimensions.

A very important feature of BS. 1490, and indeed of all the general engineering standards for aluminium and its alloys, is the clear and comprehensive system of nomenclature. It is often said by the uninformed that aluminium alloys are unintelligible because they have so many and such conflicting names. It is true that many manufacturers give their alloys trade names; such a practice is as old as industry itself, and surely no company is to be criticised for its pride and confidence in its own products. However, each supplier recognises British Standards, and sells his materials to comply with them. Therefore, an understanding of the designations in these standards is vital and, in BS. 1490, it is quoted as follows, the prefix initials LM indicating that the material is an ingot or casting :—

"In this schedule the following symbols have been adopted :—

(a) *Form of material* :—

Ingots. Alloy number with no suffix letter (e.g., LM4)

Castings. Alloy number with suffix letter according to condition of material (e.g., LM6-M)

(b) *Condition* :—

Suffix letters have been used to indicate the condition of heat treatment in which the materials are available. The suffix letters have the following significance :—

M = Material in the as-cast condition.
W = Material which has been solution-heat-treated.
P = Material which has been precipitation-heat-treated.
WP = Material which has been solution and precipitation-heat-treated, i.e., fully heat-treated."

The compositions and specified properties of aluminium casting alloys to BS. 1490 are given in Table I.

Standards for Wrought Products in Aluminium and its Alloys

The problem of standardising wrought forms of aluminium and its alloys is greater than in the case of castings, for the simple physical reason that there are more of them. Thus, when the series of British Standards for Wrought Aluminium and its Alloys for General Engineering Purposes was published between 1948 and 1951, there were eight, as follows :—

BS. 1470 Sheet and strip.
BS. 1471 Tubes.
BS. 1472 Forgings.
BS. 1473 Wire for rivets.
BS. 1474 Welding wire.
BS. 1475 Wire for general purposes.
BS. 1476 Bars, rods, and sections.
BS. 1477 Plate.

The compositions of the various grades of pure metal and the alloys are given in Table II, and it must be noted that, while not all alloys are standardised in all the different wrought forms, the composition of any particular material is the same in any form in which it is made. Its mechanical properties may, of course, differ slightly in different forms, and this is brought out in Tables III and IV, which give, as examples, the principal mechanical properties specified in BS. 1470 and 1476.

The system of nomenclature in these standards has points of similarity with that of BS. 1490 but, in view of its importance and certain fundamental differences in terms resulting from the contrasting nature of wrought and cast products, it is best to consider it separately. Quoted from BS. 1477, the system is as follows :—

(a) *Form of material* :—

E = Bars, rods, and sections (BS. 1476).
S = Sheet (up to and including 0·252 in.) and strip (up to and including 0·192 in.) (BS. 1470).
C = Clad sheet and strip (BS. 1470).
P = Plate (BS. 1477).
PC = Clad plate (BS. 1477).
T = Tubes (BS. 1471).
F = Forgings (BS. 1472).
R = Wire for rivets (BS. 1473).
W = Welding wire (BS. 1474).
G = Wire for general purposes (BS. 1475).

(b) *Heat treatment* :—

For aluminium alloys, the following symbols have been adopted throughout :—

N = Non-heat-treatable alloys.
H = Heat-treatable alloys.

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Thus, the letters " NP " indicate non-heat-treatable alloys in the form of plate. The letters " HS " refer to heat-treatable alloys in the form of sheet and strip.

(c) *Condition* :—

Suffix letters have been used to indicate the temper or condition of heat treatment in which the materials are available. These symbols, for aluminium and non-heat-treatable alloys, are as follows :—

O = Material in the annealed condition.

¼H, ½H, ¾H, H } The various harder tempers in the case of sheet and strip, plates, tubes, and wire.

M = Material in the " as-manufactured " condition, e.g., as-rolled, as-extruded, straightened and/or drawn to size, or as-forged in the case of forgings.

For the heat-treatable alloys the suffix letters have the following significance :—

O = Material in the annealed condition.

M = Material in the " as-manufactured " condition, e.g., as-rolled, as-extruded, straightened and/or drawn to size, or as-forged, without subsequent heat treatment of any kind.

T = Material which has been solution-treated and requires no precipitation treatment.

W = Material which has been solution-treated and will respond effectively to precipitation treatment.

WP = Material which has been solution-treated and precipitation-treated.

P = Material which has been precipitation-treated only (at present applicable only to castings).

(d) *Numerical classification* :—

The different grades of aluminium and aluminium alloys are listed under numbers, and the same number has been used to indicate any given grade of aluminium or any aluminium alloy in whatever form it may be obtainable. Aluminium has been given the classification 1, the three grades being identified by the suffix letters A, B, and C.

(e) *Examples* :—

The following are examples of the nomenclature specified above :—

T1C-½H indicates pure aluminium of grade 1C in the form of tube, in the half-hard condition.

NE4-M indicates non-heat-treatable alloy No. 4 in the form of bars, rods, or sections, in the " as-manufactured " condition.

HS10-W indicates heat-treatable aluminium alloy No. 10 in the form of sheet, which has been solution-treated and will respond effectively to precipitation treatment.

HPC15-WP indicates heat-treatable aluminium alloy No. 15 in the form of clad plate, which has been solution- and precipitation-treated.

The specific clauses of the standards BS. 1470-1477 define chemical compositions and minimum mechanical properties, in various conditions of temper or heat treatment, where applicable, and varying according to size with certain products. The mechanical tests differ with different forms ; thus, certain tubes are subjected to a flattening test, rivet wire to a heading test, thin sheet to a bend test, and so on ; yet, the main properties remain the 0·1% proof stress, the tensile strength, and the elongation as a percentage on a gauge length of 2 in. or four times the root of the cross-sectional area of the specimen. The general clauses are concerned with selection of test samples, preparation of testpieces, freedom from harmful defects, and the conditions concerning retesting of material which fails to pass any test with the first specimen selected. Another important factor is the certificate of compliance, by means of which the supplier expresses to the purchaser that the material is indeed in accordance with the standard.

With wrought products, tolerances on dimensions may be as vital a quality as metallurgical excellence. Therefore, the general clauses of BS. 1470-1477 contain extensive tables of such tolerances—thickness of sheet, diameter of tube, and across-flats dimension of hexagonal bar—in some cases to more than one degree of fineness. Compliance with the standard involves compliance with these dimensions, and the grade of tolerances applicable must always be stated.

The Use and Limitations of Standards

The post-war years have seen a considerable reduction in the use of non-standard materials, both wrought and cast, and the dangers of going outside British Standards for general engineering materials are manifest. Dealing first with wrought products, which are made on expensive plant requiring long runs of production to work economically, it is obvious that small quantities of special materials will be extremely expensive, and will probably even then be unremunerative to the producer, in view of the interruption of the smooth working of equipment. From the user's point of view, quite apart from the question of cost, he is able by using a standard material to be confident that, once he has developed a technique for manipulating it, its composition, properties, and dimensions will always be within fixed limits, and he can buy such material from competitive suppliers, all producing the same standard material. Nor does this apply only to the large user, who could, in any case, test the material himself to ensure its suitability. The smaller consumer can purchase his requirements of standard materials direct or, for small quantities, through a reliable stockist.

In the case of castings, a factor enters which is less applicable in wrought production. Extrusion, rolling, forging, drawing, etc. are the province of highly capitalised manufacturers, and standardisation is as important to them as to their customers, as noted above. The small foundry requires little costly equipment, and here the British Standard is a very real protection for the user. He may be offered at a slightly reduced price castings in non-standard alloys, or which do not comply in some other respect with BS. 1490. This temptation should be resisted, as it can often lead to considerable difficulty. The experienced metallurgist, faced with some unexpected failure in cast aluminium alloy, immediately suspects that the material is non-standard, and many serious shortcomings turn out to be due to this cause. Similarly, the founder who buys his ingots to a standard is avoiding unknown causes of casting difficulty, quite apart from possible shortcomings in his own products.

In this connection, it should be borne in mind, however, that standards for semi-fabricated products in aluminium and its alloys simply aim at setting a degree of quality below which the product cannot fall, and which the user may be sure of obtaining. A standard does not give advice or information. In discussions referring to standards, a frequent criticism of BS. 1490 and BS. 1470-1477 is that they do not give sufficient information to the user ; thus, for instance, they do not tell him how to select alloys for particular applications, at what temperature to heat-treat certain alloys, what are the limiting radii of bends in sheet or plate, or which alloys are most readily weldable. It cannot be too strongly emphasised that such information is not suitable for inclusion in a yardstick of quality such as the British Standard.

Some large users may be interested in some special property of a standard alloy, which depends for its attainment on special production conditions. Earing tendency in sheet, good surface in extrusions, deep-drawing quality in strip, and close tolerances in tubes are examples of such properties. If there are special requirements of this type, the supplier should be consulted when the order is placed, and production conditions may be adjusted to give the properties needed,

TABLE I. CASTINGS—SPECIFIED COMPOSITION AND MECHANICAL PROPERTIES (BS. 1490 : 1949).

	Percentage Composition (Maximum values, unless otherwise stated)							Condition	Test-piece	Minimum Mechanical Properties	
	Cu	Mg	Si	Fe	Mn	Ni	Zn			Ultimate tensile stress, tsi	Elongation on 2 in., %
LM0 Aluminium ingots for remelting	0 2	0·05	0·5	0·6	0·2	0·1	0·1	—	—	—	—
LM1	6–8	0·15	2–4	1·0	0·6	0·5	2–4	M	S C	8 10	— —
LM2	0·7–2·5	0·30	9·0–11·5	1·0	0·5	1·0	1·2	M	S C	8 9·5	— —
LM3	2·5–4·5	0·10	1·3	1·0	0·5	0·5	9–13	M	S	9	—
LM4	2·0–4·0	0·15	4·0–6·0	0·8	0·3–0·7	0·35	0·5	M	S C	9 10	2 2
LM5	0·1	3·0–6·0	0·3	0·6	0·3–0·7	0·1	0·1	M	S C	9 11	3 5
LM6	0·2	0·10	10·0–13·0	0·6	0·5	0·1	0·1	M	S C	10·5 12	5 7
LM7	1·0–2·5	0·05–0·20	1·5–3·5	0·3–1·4	0·1	0·5–1·7	0·1	P	S C	10 12·5	2 3
LM8	0·1	0·2–0·6	4·5–6·0	0·6	0·3–0·7	0·1	0·1	W WP	S C S C	11 15 15 17	2·5 5 — 2·5
LM9	0·1	0·2–0·6	10·0–13·0	0·6	0·3–0·7	0·1	0·1	P WP	S C S C	11 15 15·5 19	1·5 2 — —
LM10	0·1	9·5–11·0	0·35	0·35	—	—	—	W	S C	18 20	8 12
LM11	4·0–5·0	—	0·25	0·25	—	—	—	W WP	S C S C	14 17 18 20	7 13 4 9
LM12	9·0–10·5	0·15–0·35	2·0	0·5–1·5	0·6	0·5	0·1	WP	—	—	—
LM13	0·5–1·3	0·8–1·5	11·0–13·0	0·8	0·5	2·0–3·0	0·1	WP WP (Special)	S C S C	11 16 9 13	— — — —
LM14	3·5–4·5	1·2–1·7	0·6	0·6	0·6	1·8–2·3	0·1	M WP WP (Special)	S C S C S C	10 12 14 18 12 15	— — — — — —
LM15	1·3–3·0	0·5–1·7	0·6–2·0	0·8–1·4	0·1	0·5–2·0	0·1	WP	S C	18 21	— —
LM16	1·0–1·5	0·4–0·6	4·5–5·5	0·6	0·5	0·25	0·1	W WP	S C S C	11 13 15 17	2 — — —
LM17	0·1	0·10	10·0–13·0	0·6	0·5	2·5–3·5	0·1	M	S C	12 16	2 3
LM18	0·1	0·10	4·5–6·0	0·6	0·5	0·1	0·1	M	S C	12 16	2 3
LM19	2·0–4·5	0·2–1·5	0·7	0·8	0·1–0·5	Cd 0·5–2·5	0·2	W	S C	14 17	3 5
LM20	0·4	0·15	10·0–13·0	0·7	0·5	0·1	0·2	M	S C	10·5 12	3·5 5

S = sand-cast ; C = chill-cast.

with a standard product. This is, of course, feasible only with large orders, often at a reasonable price differential.

Under this heading of the use of standards, a word should be said about resistance to corrosion. Although this property is affected by design considerations, the main control of corrosion resistance of the pure metal or an alloy is by close attention to composition and the placing of low maxima on permissible contents of deleterious impurities. This is an example of the use of standards to ensure good performance in a direction which is very difficult to assess by other means.

KEEPING STANDARDS UP-TO-DATE

It is the policy of the B.S.I. to review standards at least every five years, and during the past two years much time has been spent both by the Institution and by technical committees within the industry itself in a complete and thorough redrafting of these standards for semi-fabricated products in aluminium and its alloys, to ensure that they are abreast of the present stage of technical knowledge in both the producing and using industries. The results of this work should appear as revised standards during the course of 1955.

TABLE II. COMPOSITION OF WROUGHT MATERIALS.

	Percentage Composition (Maximum values, unless otherwise stated)							
	Cu	Mg	Si	Fe	Mn	Ni	Zn	Cr
1A	0·02	—	0·15	0·15	—	—	—	—
1B	0·05	—	0·3	0·4	0·05	—	—	—
1C	0·1	—	0·5	0·7	0·1	—	0·05	—
N3	0·15	—	0·6	0·75	1·0–1·5	—	0·1	—
N4	0·15	1·75–2·75	0·6	0·75	0·5	—	0·1	0·5
N5	0·15	3·0–4·0	0·6	0·75	1·0	—	0·1	0·5
N6	0·15	4·5–5·5	0·6	0·75	1·0	—	0·1	0·5
N5/6	0·1	3·0–5·5	0·6	0·7	1·0	—	0·1	0·5
N7	0·15	6·5–7·5	0·6	0·75	1·0	—	0·1	0·5
H9	0·15	0·4–0·9	0·3–0·7	0·6	—	—	0·1	—
H10	0·15	0·4–1·5	0·75–1·3	0·6	1·0	—	0·1	0·5
H11	1·0–2·0	0·5–1·25	0·75–1·25	0·75	1·0	0·25	0·20	—
H12	1·8–2·5	0·6–1·2	0·5–1·3	0·6–1·2	0·2	0·6–1·4	0·2	—
H13	1·5–3·0	0·2–0·5	0·7	0·7	0·5	0·25	0·2	—
H14	3·5–5·0	0·4–1·2	0·7	0·7	0·4–1·2	0·25	0·2	—
H15	3·5–4·8	0·6	1·5	1·0	1·2	0·25	0·2	—
H17	3·5–4·5	1·2–1·7	0·6	0·6	—	1·8–2·3	0·2	—
H18	1·8–2·5	1·2–1·8	0·5–1·3	0·6–1·2	0·2	0·6–1·4	0·2	—

At this stage, it is possible only to give examples of the types of adjustments that have been made. It should be clearly understood that no revolutionary changes have been necessary; nevertheless, new alloys have been added, and others, of diminishing application, deleted. On the castings side, for instance, a free-cutting alloy of limited use, i.e., LM19, will no longer appear, but a pressure die-casting aluminium-copper-silicon alloy has been added, reflecting the increasing importance of this type of casting. A particularly interesting addition is an Al—5% Si—3% Cu alloy similar to LM4-M, but permitting a zinc content of up to 2·0%. With the increasing availability of wrought aluminium alloy scrap with appreciable contents of zinc, it became obvious that such an alloy as the above would be a valuable outlet; however, extensive foundry trials were first made, and many samples were tested for strength, ductility, and corrosion resistance; work was done both by a representative body of the aluminium-alloy refiners and by a research association. The research proved that the alloy was satisfactory in all respects and merited inclusion in BS. 1490.

To take an example from the wrought materials, the heat-treatable aluminium-magnesium-silicon alloys have hitherto been represented in BS. 1470-1477 solely by the versions H9 and H10. H9 has medium strength only, and is used in low-stressed applications. The composition limits of H10 are wide and cover alloys with and without added manganese, an element which confers improved proof and ultimate stresses on the alloy in the fully heat-treated condition. No provision was made for the aluminium-magnesium-silicon alloys with small proportions of added copper and either chromium or manganese, which extensive transatlantic experience and much testing in Great Britain have shown to be valuable to the structural engineer. In the revised versions of these standards, all three types will be included, i.e., low manganese, copper together with chromium or manganese, and about 0·75% added manganese, the last being required to have in the fully heat-treated condition a proof stress and ultimate strength 1 tsi higher than the first two. The nomenclature question has been solved by naming the last two alloys H20 and H30, and printing the specific requirements relating to them immediately following those covering H10.

The above are examples only; a consideration of the revised standards and the changes they make must await their issue in the near future.

STANDARDS FOR MANUFACTURED ARTICLES

The B.S.I. division concerned with standards for aluminium and its alloys is the Engineering Division, and the Industry Committee directly responsible for BS. 1490 and BS. 1470-1477 is the Non-Ferrous Metals Industry Committee, although the work of preparation and revision is in the hands of a Technical Committee. The main user of these standards is in his turn the manufacturer of products of which aluminium or its alloys form the whole or part, and for which it is often possible to prepare British Standards. The products concerned may be component parts of other manufactured articles, as, for instance, nuts and bolts, or they may be completed goods ready for sale to the ultimate user.

The merits of standards of this type are the same as those of standards for aluminium and its alloys in semi-fabricated forms; in other words, they give the manufacturer a yardstick to which to work and the user an assurance that the quality of his purchase will not fall below a certain defined and specified minimum. In many cases,

TABLE III. SPECIFIED MECHANICAL PROPERTIES (BS. 1470).

BS. 1470 Sheet & Strip	Condition	Minimum Mechanical Properties		
		0·1% Proof stress, tsi	Ultimate tensile stress, tsi	Elongation on 2 in., %
S1A	O	—	4–5	35
	¼H	—	6–7·5	8
	H	—	8	5
S1B	O	—	4·5–6	30
	¼H	—	6·5–8	8
	H	—	8·5	5
S1C	O	—	5–6·5	30
	¼H	—	6–7·5	12
	½H	—	7–8·5	7
	¾H	—	8–9·5	5
	H	—	9	3
NS3	O	—	6–7·5	30
	¼H	—	7·5–9·5	12
	½H	—	9–11	7
	¾H	—	10·5–12·5	5
	H	—	11·5	3
N4	O	—	11–14	18
	½H	12	15	5
NS5	O	6	14	18
	¼H	11	17	8
NS6	O	8	17	18
	¼H	14	19	8
NS7	O	9	20–23	18
HS10	W	7	13	15
	WP	15	19	8
HS14	T	14	24	15
HC14	T	14	24	15
HS15	W	14	24	15
HC15	W	14	24	15
	WP	20	26	8

however, the resemblance ends here. While engineering components, such as nuts and bolts, are relatively easy to standardise, since they are made of standard materials to dimensions upon which tolerances may be set, consumer goods often present much greater difficulties, and indeed in some cases no really satisfactory way of standardising them has been found. Sometimes, the only possible approach would be to include a test simulating service conditions, but considerably accelerated in effect; such tests, however, are difficult to devise and may be misleading in their results. Nevertheless, where it is possible to lay down details of construction and permissible variations, very satisfactory standards for consumer goods may be enunciated, and it is often feasible to include in them simple tests to verify certain qualities.

In these "application" standards, the materials specified must, wherever possible, be standard materials, selected with a view to technical suitability, compatibility with each other and the service environment, and economic considerations. Requirements for special non-standard materials should be rigorously excluded, except in very rare circumstances where their use is unavoidable.

In the following review, some examples are given of the fields of "application" standards into which aluminium and its alloys have made their way; the number is constantly increasing, partly because of the continual preparation of new standards by the B.S.I., and partly as the constant industrial development of the metal confirms its new uses, and so necessitates its entry into existing standards. No attempt has been made at an exhaustive or comprehensive survey, but only to give an indication of this aspect of aluminium in standardisation.

TABLE IV. SPECIFIED MECHANICAL PROPERTIES (BS. 1476).

BS. 1476 Bars, Rods & Sections	Condition	Size	Minimum Mechanical Properties		
			0·1% Proof stress, tsi	Ultimate tensile stress, tsi	Elongation on 2 in., %
E1A	M		—	3·5	30
E1B	M		—	4	25
E1C	M		—	4	20
NE4	M		—	11	18
NE5	M	Up to 2 in.	6	14	18
		Over 2 in.	5	14	18
NE6	M	Up to 2 in.	8	16	18
		Over 2 in.	7	16	18
NE7	M	Up to 2 in.	9	20	18
		Over 2 in.	8	20	18
HE9	M		—	7	15
	W		5	9	18
	WP		10	12	12
HE10	W		7	12	18
	WP		15	18	10
HE11	W	All sizes	10	17	15
	WP	Up to & incl. ¾ in.	19	24	8
		¾ in. to 3 in.	20	25	8
		Over 3, up to 6 in.	20	25	8
		Over 6 in.	17	23	6
HE14	T	¾ in. & under	14	24	15
		Over ¾, up to 3 in.	15	25	15
		Over 3, up to 6 in.	15	25	12
		Over 6, up to 8 in.	14	24	10
HE15	W	¾ in. & under	14	24	15
		Over ¾, up to 3 in.	15	25	15
		Over 3, up to 6 in.	15	25	12
		Over 6, up to 8 in.	14	24	10
	WP	¾ in. & under	24	28	8
		Over ¾, up to 3 in.	26	30	8
		Over 3, up to 6 in.	26	30	8
		Over 6, up to 8 in.	24	28	8

Building and Structural Engineering :—

The building and structural-engineering industries are very important users of aluminium and its alloys in many forms, and have been prominent in the preparation of British Standards for the products they employ. B.S. 1161 "Aluminium and Aluminium-Alloy Sections" covers standard ranges of angles, channels, tees, and I's for structural use, all of which are readily available from the extrusion manufacturers, and details are given of the section properties of each type and size. Since 1951, BS. 1139 "Metal Scaffolding" has covered aluminium-alloy tubes and fittings, in addition to steel. Aluminium-alloy ladders are covered by BS. 2037 "Ladders, Steps and Trestles for the Building and Civil Engineering Industries."

A large application of aluminium-alloy sheet is for roofing and siding, and work will shortly commence on the standardisation of corrugated and troughed sheets for these purposes. A standard is already available for roofing nails, screws, etc. for use with these sheets, namely BS. 2465 : 1954 "Aluminium Fixing Accessories for Building Purposes." Rainwater goods of two grades have been standardised, the lighter type made from sheet in BS. 1543 : 1949 "Wrought Aluminium Rainwater Goods," and a heavier variety in BS. 1430 : 1947 "Aluminium Rainwater Goods—Cast and Extruded." Work is now in hand by the B.S.I. to revise both these standards completely and to combine them in one document.

Aluminium paints are highly esteemed both as primers for wood and protective paints for steelwork, and BS. 388 : 1952 covers the "leafing" flake in powder and paste, which forms the basis of such paints.

Finishes for aluminium itself are very numerous, but a decorative and protective process applicable almost exclusively to aluminium is anodising. BS. 1615, in use since 1949, covers this electro-chemical finish for various fields of exposure, and much work is currently being done to extend its scope and keep it abreast of recent developments; a revised version is expected to be published within some months.

Electrical Applications :—

An important property of aluminium is its high electrical conductivity; a standard is in an advanced stage of preparation for aluminium of electrical purity in the form of wire, and this will be followed by other wrought forms. At the same time, a standard is being prepared for aluminium insulated cables, while aluminium sheathed cable is already covered by BS. 480, Part 2, 1954 "Aluminium Sheathed Cables for Working Voltages up to and including 22 kV." BS. 215 : 1954 "Hard Drawn Aluminium and Steel Cored Aluminium Conductors for Overhead Power Transmission," is at present undergoing extensive revision; it is concerned with the conductor which now forms a very high proportion of the grid in Great Britain and of which much is exported yearly.

Aluminium busbars are included in BS. 159 "Busbars and Busbar Connections in Air, Oil, and Compound."

A continuing feature of the post-war years has been the modernisation of street lighting, and many of the lanterns are in aluminium alloy in accordance with BS. 1788 : 1951.

Packaging :—

Despite the fact that most "silver paper" is now

aluminium foil, manufacturers and users have not favoured the preparation of a comprehensive standard for the product, preferring to deal with each application separately. Since 1950, BS. 1683 has been in use, covering coated aluminium foil for cheese-wrapping; the aluminium foil/vegetable parchment laminate, now becoming so popular for wrapping butter and other food products, will very shortly be standardised. Collapsible tubes are covered by BS. 2006 : 1953.

Many packaging applications of aluminium and its alloys are described in the British Standard Packaging Code, BS. 1133, first issued during the war and later the subject of extensive revision, which is still continuing. There remains, however, considerable scope for individual specifications for packages of different types, although the difficulties of standardising such a variety of goods and materials are considerable.

Joining :—

One of the greatest recent advances in aluminium technology has been in the field of joining, and some of the developments have found their way into British Standards. Small rivets, up to $\frac{7}{16}$ in. in diameter and with various heads, are covered by BS. 641 : 1951, while sizes from $\frac{1}{2}$ in. to 1 in. are the subject of BS. 1974 : 1953 " Large Aluminium-Alloy Rivets."

An important series of British Standards is concerned with welding and brazing. BS. 1616 : 1950 is devoted to aluminium electrodes for metal arc welding, while filler wire for gas welding is covered by BS. 1453 : 1952. The process of gas welding certain aluminium alloys for aircraft is standardised in BS. 1126, published during the war and now in need of revision. Testpieces for the inspection of spot welds in aluminium alloy are given in BS. 1138.

Aluminium and its alloys are included in BS. 1723 : 1954 " Brazing," which lays down procedure in this method of joining and refers to BS. 1942 : 1953 " Aluminium Filler Alloys for Brazing " for the necessary brazing alloys.

Aircraft :—

Aluminium and its alloys for aircraft construction are not usually purchased to general engineering standards, in view of the especially onerous inspection conditions necessitated by service in modern high-performance aircraft. Therefore, in addition to the DTD series of provisional specifications mentioned earlier, well-established aircraft alloys are covered by the British Standard " L " series, which applies to both wrought and cast materials, and each of which is confined to one material in one condition of heat-treatment or temper. Two standards in this series are concerned with testing and inspection, i.e., L100 for wrought materials and L101 for castings, which now govern not only the " L " standards but also the " DTD " series.

The " L " series of standards is not, of course, classifiable as " end-use " standards, since it covers materials from which goods are manufactured; it is, however, tied to one market only, and is mentioned here for completeness, and also to give opportunity to give the following warning :—The designations of the " L " and " DTD " series are much misused, principally by purchasers of materials, but also in some cases by suppliers. They should not be applied to alloys for any use other than aircraft construction.

In addition to the " L " series, the B.S.I. has standards for various details and parts in aluminium alloy for aircraft use, such as rivets, nuts and bolts, electrical components, etc., and these are true " application " standards.

Codes of Practice

Another type of standard document, published by the B.S.I. but sometimes prepared principally by other bodies, such as the great engineering institutions, is the Code of Practice, which is a standard description of the correct method of design, installation, and maintenance of buildings, electrical facilities, and similar engineering equipment. These Codes make reference to British Standards for materials and components, and several include aluminium. Additionally, requests are being made for the preparation of Codes devoted entirely to aluminium, in certain fields. Although Codes of Practice may not yet be as numerous as British Standards, their value is obvious, particularly as a protection to the customer, and every effort is being made to introduce aluminium into them, where appropriate.

International Standardisation

In a world which is getting smaller, where, for instance, aluminium ingots produced in Canada may be alloyed and rolled into sheet in England, and used in Africa, and where American aircraft may have to be serviced in Europe, some form of international standardisation is becoming increasingly desirable. Nevertheless, although most countries have their own standards for aluminium and its alloys, these standards differ from each other in many ways. Indeed, they are completely different documents, except insofar as thinking in the larger, older aluminium industries of the world has influenced thinking in the newer, so that sometimes a country may adopt the standards of another as its own.

To take examples of how views differ, the American aluminium-copper-magnesium fully heat-treated alloy used in aircraft has a higher magnesium content than the British, and is thought by producers here to be more difficult to work. Although the French make a casting alloy in other respects in the same class as the British aluminium — $4\frac{1}{2}\%$ copper heat-treatable alloy, they require a small addition of magnesium, whereas, in Great Britain, magnesium content is kept as low as possible. Aluminium-zinc-magnesium naturally age-hardening casting alloys are popular in the U.S.A. and Europe, but little has been done with them in Great Britain. Only fairly recently have the Americans shown appreciable interest in the aluminium-magnesium alloys containing more than about 2% magnesium, though such alloys have been the basic ship- and boat-building alloys in the United Kingdom for decades. F. H. Smith* has indicated the differences and points of similarity in the standards for aluminium casting alloys published throughout the world; to do the same for wrought alloys would be a Herculean task, in view of the many different wrought forms involved.

Further complications arise with the different nomenclature in vogue in different countries, the different systems of weights and measures, and the varying testpieces and methods of producing them. Great Britain and the U.S.A. use a 2 in. gauge length; on the Continent, gauge lengths vary. Similarly, in England, strengths are normally measured in tons per square inch, as against pounds per square inch in the U.S.A. and kilograms per square millimetre on the Continent.

Attempts are now being made to meet this crying need for regularisation. In January of this year, the first meeting was held in Paris of a committee of the International Standards Organisation, which has been charged with the task of internationally standardising aluminium, magnesium, and their light alloys. The magnitude of the work is fully realised, but a good start has been made, and—even more valuable—views were interchanged, and each country's representatives given the opportunity of seeing the others' point of view. Although many years must of necessity pass before this work is completed, useful results should appear as further meetings are held.

*" Standards for Aluminium Casting Alloys," *Light Metals*, Vol. 16, 1953, pp. 371-372, 398, and Vol. 17, 1954, pp. 17-20, 51-54, 89-90, 114-116.

The Welding of Aluminium and its Alloys

By J. F. LANCASTER, B.Eng., A.I.M.*

IN the early years of this century Heraeus in Germany was able to make very handsome aluminium vessels, the seams of which were joined by hammer welding. This highly skilled operation was carried out by chamfering the edges of the sheet, heating them until a stick of pinewood rubbed on the surface left a black mark, and then hammering the lapped joint flush with the parent sheet. Hammer welding was effective but slow and, after Schoop in 1907 patented a flux which made oxy-acetylene welding possible, it survived only a short time. On the other hand, gas welding (Fig. 1) has had a long and useful life and is by no means completely out of date, despite the fact that the process is essentially the same to-day as when it was invented.

Fig. 1. **Gas welding an aluminium transport tank.** The mate is maintaining a gap, in order to prevent the sheets from overlapping.

Carbon arc welding has been advocated for aluminium from time to time, but there is little evidence of its having been used on any scale, except, perhaps, as an automatic process. Metallic arc electrodes were developed during the 1930's and were greatly improved by the introduction of extruded coatings. In the early days, attempts were made to apply this method to the fabrication of pure aluminium for chemical plant but, generally speaking, it was unsuitable for such work. The pure aluminium electrode was, and still is, difficult to handle and the amount of setting up required did not justify the results obtained. The Al—5% Si rod was much more tractable and found a wide application for structural work and filler welding, particularly in the United States. Metallic arc welding was also developed to a high level of efficiency in Norway, where it has been used in shipbuilding.

The resistance welding of aluminium can claim a longer history than the fusion process—West[1] dates the origin of flash- and butt-welding as 1890 or before—but it first came into real prominence during World War II, when spot welding was used for the assembly of aircraft components.

It is by no means easy to obtain consistent spot welds in light alloys. Because of its high thermal and electrical conductivity, aluminium requires the use of high-capacity machines with close control of the welding variables, and the nature of the oxide film makes pre-cleaning of the sheet essential. A great deal of research effort was put into spot welding during this period but, in spite of the advances in technique which were made, it has found relatively little use in the post-war years, even in the aircraft industry. General engineering applications for resistance welding are also relatively rather limited. Some sheet-metal work is spot-welded, and flash butt-welding is used for joining sections, notably in the manufacture of window-frames. For the last decade, however, the main interest both in research and industrial development has centered around fusion welding.

The gas torch remained the essential tool for joining aluminium sheet and plate, until the arrival of inert-gas welding in the late 1940's caused a revolution in fabrication methods. The two inert-gas processes have the solid advantage of covering the whole range of fused welding needs. Argonarc welding (Fig. 2) is functionally similar to gas welding in that heat and filler wire are applied separately, thus permitting a nice control over penetration and reinforcement. A water-cooled torch is used, the essential part of which is a tungsten electrode surrounded by a gas hood, through which inert gas (argon in Great Britain) flows to protect the weld pool and electrode from atmospheric attack. The power source is a special-purpose a.c. unit, comprising transformer, condenser bank to prevent arc rectification, and high-frequency ioniser to ensure re-ignition. Oxide is dissipated from the metal surface during the electrode positive half-cycle, so that no flux is needed.

The complementary process consists essentially of a bare wire electrode surrounded by a stream of inert gas, and functionally resembles arc welding with coated electrodes. Equipment consists of a reel from which wire is fed at a controlled speed through the "gun," with a d.c. generator having its negative pole connected to the work. By using a relatively fine wire and high current, a spray-type metal transfer is obtained, enabling welding to be carried out in all positions. Moreover, the arc is, within limits, self-adjusting; in other words, if the wire feed speed increases, the burn-off rate also increases, so that the arc is maintained. This makes the gun easy—perhaps deceptively easy—to use. Once again, the oxide film is dissipated by the arc and no flux is required. The nomenclature of this method is confused, commercial equipment being known variously as Aircomatic, Sigma, Argonaut, and Fillerarc, general names being inert-gas-shielded metal arc and self-adjusting arc. The latter term will be used here because it is slightly less cumbersome than the former term and also to distinguish the process from that in which a heavy feed wire is used and where the self-adjusting mechanism does not operate.

Apart from its advantage of all-position welding, the self-adjusting arc method has the merit of being fast and semi-automatic. On the other hand, it does not give easy control of penetration and at present cannot be used for aluminium butt or fillet welds in metal thinner than $\frac{1}{8}$ in.; furthermore, the welds tend to be porous. In spite of this, they are decidedly superior to metal arc welds and, insofar as essential properties are concerned,

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Fig. 2. **Argonarc welding of aluminium, 1-in. in thickness.** Two operators work together to maintain heat. This procedure has been outdated by the introduction of automatic "controlled-arc" machines.

do not fall much behind those made with the argonarc torch.

RESEARCH PROGRESS

These remarkable developments have opened up many new possibilities both for the metallurgist and for the production engineer, and at the same time have given rise to a crop of new problems. On the one hand, for example, many of the alloys which previously were difficult or impossible to join by fusion welding may now be used or at least considered for use; on the other hand, the newer methods can give rise to defects, such as oxide films, which were not prevalent with gas or metal arc welding. Add to this the increased use of aluminium and the demand for aluminium vessels and structures to withstand more severe conditions, and it will be seen that the need for research is acute. Fortunately, this demand is being met to a very large extent, and the British Welding Research Association (B.W.R.A.), and the Electrical Research Association (E.R.A.) in particular are playing an important part in developing equipment and solving outstanding problems.

Typical of this work is a series of papers recently published by B.W.R.A.[2] The problem of welding heat-treatable alloys, which is of importance for aircraft and structural work, is being tackled systematically. There are two main problems associated with these materials, i.e., cracking in or adjacent to the weld, and the low strength of welds due to weakness in the weld-metal itself and softening of the heat-affected zone. The cracking problem is perhaps the most immediately important, since it is a most serious and insidious defect and since the only heat-treatable alloy at present welded to any considerable extent, H.10, is very crack-sensitive. The metallurgical aspects of cracking in aluminium alloys were studied extensively by the Aluminium Development Association (A.D.A.) team at Birmingham University, who showed that it occurred most acutely in alloys having a long solidification range—in general, those containing relatively small amounts of alloying elements.

In the H.10 type of alloy, crack-sensitivity is reduced as the silicon content is increased, and at just over 3% silicon becomes negligibly small, so that for some years it has been customary to weld this material with a 5% silicon electrode or filler wire. Recent experience has shown, however, that serious cracking can still occur even under these circumstances. Investigation of this type of failure brought to light the rather surprising fact that in unprepared butt welds the dilution of filler rod by parent metal ranged between 65% and 90%. In the case of H.10 welded with 5% silicon electrodes, this brings the weld-metal composition into the range of 1·5 to 2·5%, the region where cracking would be expected. Subsequently, Pumphrey[3] confirmed these results and has suggested that for safe welding with dilutions up to 80% (i.e., all fillet and most butt welds) an electrode containing at least 10% silicon should be used. This would seem to settle the matter, as far as structural work is concerned, but for pressure vessels, where the use of high-silicon electrodes would not be permissible because of the possibility of corrosion, H.10 remains a difficult material to weld. This is unfortunate, since in most other respects it has very attractive properties.

A good start has also been made in developing methods for the welding of aircraft alloys, including the "super-dural" type HS.15 and the high-strength copper-magnesium-zinc alloy DTD 687. In both these materials a weld efficiency of more than 95% can be obtained by argonarc welding with a parent-metal filler wire and carrying out complete heat treatment after welding. This is promising but not very practical, as welds made with a parent-metal filler crack under restraint, and because full heat treatment of a welded structure, involving as it does quenching from about 500° C, would not often be possible.

However, other filler materials have been tested, and amongst those reported the 6% magnesium rod gives the best result—a weld efficiency of 55 to 60% as-welded, and in DTD 687 about 80% when heat-treated. More work can be done along these lines, but the possibility of developing an alloy of high strength and good weldability must not be forgotten. Some years ago Herenguel reported the production of an aluminium-magnesium-zinc alloy (T.35) which does not anneal in the heat-affected zone after welding, and which regains its strength in this region after ageing at room temperature over a period of three months.[4] The ultimate tensile strength of T.35 is only about 20 tsi and is not, therefore, very attractive, but at least it demonstrates that a loss of strength due to welding is not inevitable.

The work on heat-treatable alloys has led to a re-examination of the problem of heat flow in welding. Wells has shown that the heat flow in a plate whose width is not less than 20 times that of the weld will have a heat-flow pattern for all practical purposes identical with that of an infinitely wide plate.[2] This is, of course, essential information for the investigator and may be equally valuable in the preparation of test plates for inspection purposes. Of more general interest is the development of the "weld characteristic" $vd/4\alpha$, where v is the welding speed, d is the fused width, and α is the thermal diffusivity of the material. The value of this expression gives the heat input rate to the weld; if $vd/4\alpha$ is less than 0·1, the weld has a low heat input and the heat spread over the plate is large, whereas, if it is greater than 1, heating will be efficient, the heat-affected zone narrow, and the cooling rates high. An example of the use of this theoretical work will be given later.

Insofar as the non-heat-treatable alloys are concerned—in particular, the aluminium-magnesium alloys—the situation is very satisfactory. These materials are of great value where good general properties and reasonable cost are more important than high strength-weight ratio, for example in ship superstructures and for pressure vessels and tanks. With gas welding, porosity occurs adjacent to the weld, reducing the weld efficiency, and with magnesium contents up to 3% cracking can occur. Metal arc welds are better, and indeed this process has been used very successfully by shipbuilders in Europe, though skill is required to handle the electrodes and full-strength joints cannot normally be obtained. With both the inert-gas processes, on the other hand, welding is almost as easy with pure aluminium, and a weld efficiency of 100% is quite normal, provided that the joint is free from defects. This has resulted in the aluminium-magnesium alloys being used both for structures and in the chemical industry to a greater extent than would otherwise have been possible.

WELDABILITY OF ALUMINIUM ALLOYS.

Alloy		Nominal Composition, %	Welding Process	Filler Wire	Weldability
Description	DTD or BS. Specification				
Pure aluminium	S1A, S1B, S1C	99·8, 99·5, 99·0 aluminium	Gas, carbon arc, argonarc, self-adjusting arc	Parent metal	Good.
Aluminium-1¼% manganese	NS3	1·25 Mn	Gas, carbon arc, argonarc, self-adjusting arc	1·25 Mn	Good.
Aluminium-magnesium	NS4, NS5, NS6	2·0 Mg 3·5 Mg 5·0 Mg	Gas	5·0 Mg	Fair, but joint strength may be impaired by porosity in the heat-affected zone.
			Metallic arc	5·0 Si	Fair; cannot obtain full strength in butt-welds with 5·0% Si rod; 5·0% Mg rod not very satisfactory.
			Argonarc and self-adjusting arc	5·0 Mg	Good, but requires more care than pure aluminium because of tenacity of oxide film. Use special high-purity gas for argonarc welding.
Anticorodal H10	HS10	0·75 Mg 1·0 Si	Metallic arc	12·0 Si	Fair; may be used where full strength is not required; not much danger of cracking.
			Argonarc and self-adjusting arc	Parent metal	Poor; cracking may be severe.
				5·0 Mg	Better, but cracking may still occur at the weld boundary.
				12·0 Si	Fair; not much danger of cracking; weld quality better than with metallic arc.
Duralumin	HS14	4·0 Cu 0·6 Mg 0·5 Mn	Argonarc and self-adjusting arc	Parent metal	Poor; cracks in weld and at weld boundary if under restraint.
Super-duralumin	HS15	4·4 Cu 0·6 Mg 0·7 Si 0·6 Mn		5·0 Si	Cracking may be eliminated, but weld efficiency low.
High-strength aluminium-magnesium-zinc, type 75S	DTD 687	0·4 Cu 2·7 Mg 0·5 Mn 5·3 Zn	Argonarc and self-adjusting arc	Parent metal	Cracking somewhat less severe than with H10 and duralumin and may be controlled under laboratory conditions. As-welded efficiency about 50%; after full heat treatment 90%.
				5·0 Mg	Fair; as-welded efficiency about 50%.
				5·0 Si	Avoids cracking but weld efficiency low.

One outstanding metallurgical problem which remains unsolved is that of porosity in the self-adjusting arc process. In downhand welding it is possible to eliminate gross porosity almost entirely by maintaining a long arc, and the residual micro-porosity has little or no effect on the properties of the joint. In positional, fillet, and corner welds, however, it is often impossible to maintain a long arc, and gross porosity can develop. In metal arc welding, porosity is, if anything, worse than with the self-adjusting arc process. The prime cause is almost certainly hydrogen, derived in the one case from a hydrated oxide film on the wire and in the other from combined moisture in the electrode coating, but the reason why aluminium is so very sensitive to hydrogen remains to be discovered. It should be remembered that, in the welding of mild steel, electrode coatings containing substantial amounts of hydrogen are used and sound welds are obtained without difficulty. At the other end of the scale, pure copper welded by the argonarc process is grossly porous, the gas in the pores being largely hydrogen, in spite of the fact that the amount of hydrogen in the arc is minute. The explanation of these wide differences in behaviour may not be simple, and it is to be hoped that current research will throw some light on the subject.

WELDING IN PRODUCTION

Although much remains to be done to perfect aluminium welding from a metallurgical point of view, the production engineer has now a much wider range of joining methods and a correspondingly greater freedom of action. Of the fusion welding processes already mentioned, gas, metal arc, argonarc, and self-adjusting arc welding are in use at present, and this is perhaps a useful time to attempt to assess their relative merits.

Gas welding lacks the appeal of novelty, but it remains the best method for making butt welds in pure aluminium, where distortion is unimportant and where the presence of flux can be tolerated. It is faster than argonarc welding; on ¼-in. plate a normal gas-welding speed is about 12 inches per minute, whereas good argonarc welds are made at 4 to 6 ipm. A rough and inaccurate fit can be tolerated without much detriment to weld quality. The effect of flux inclusions on the corrosion resistance of butt welds has probably been exaggerated, since corrosion tests carried out by the A.P.V. Laboratories have so far shown little to choose between gas and argonarc welds; indeed, gas welds have been slightly more resistant to attack by mains water and mildly saline solutions. In spite of this, the amount of gas welding is decreasing every year. The reasons are not hard to find :—Gas welding is unsuitable for making fillet welds and a great deal of hand work is required in shaping up a job, so that this type of joint is avoided. It is equally unsuited to production methods involving jigs and backing bars, as any loss of heat near the joint makes fusion of the metal difficult. Thus, not only does the process itself demand a skilled welder, but it calls for a high degree of craftsmanship in metal working. The need for skill is by no means lacking when inert-gas welding is used, but most of the hand shaping can be avoided by suitable design, and work can be set up in jigs, thus making it possible to apply modern production methods in a field where the craftsman previously reigned supreme. This tendency is cumulative in its effect, and before many years have passed it may be difficult to find a good gas welder, however desirable the process may be.

For chemical and food plant made of aluminium alloys, and for similar work involving fillet welds, one of the inert-gas processes must be used. As a general rule, argonarc welding is best for thicknesses up to $\frac{3}{16}$ in., and self-adjusting arc welding for $\frac{1}{4}$ in. and thicker, provided that the weld can be backed. For unbacked welds—for example, in large butt-welded vessels—there are several possibilities :—Double-operator argonarc welding may be used up to $\frac{1}{2}$ in., and for thicker sections a double-operator argonarc root pass can be made and the joint filled by the self-adjusting arc process. Alternatively, the joints can be welded from one side by the self-adjusting arc, using an edge preparation with a heavy root face to prevent over-penetration. The reverse side is then chipped out and completed, using the same equipment.

Where a choice has to be made between argonarc and self-adjusting arc welding it is not easy to give firm guidance. Both types of weld, if badly made, can contain oxide films, although a continuous film, which has a disastrous effect on strength, is more prevalent with the double-operator argonarc technique. In addition, self-adjusting arc welds always contain micro-porosity and may have some degree of gross porosity. For this reason the argonarc process is usually specified for severe conditions of corrosive attack or stress. As far as corrosion resistance is concerned, there are at present no data to assess the true properties of the joint, but, in relation to stress, tests have shown that porosity, unless it is concentrated along the centre line or weld boundary, has little effect on strength ; certainly, it has no effect on leak-tightness. Experience has shown that self-adjusting arc welds are perfectly vacuum- and pressure-tight. In practice, thickness is an important factor in making the proper choice. Up to and including $\frac{1}{4}$-in. plate, it is easy to make perfect argonarc welds, but in thicker material, above $\frac{1}{2}$ in. particularly, defects such as oxide films, tungsten inclusions, and (rather surprisingly) porosity are likely to appear, and self-adjusting arc welds are on the whole superior. Fortunately, this choice coincides with production requirements. Argonarc welding is at best a slow process, but on 1-in. thick plate it is inexpressibly tedious.

When argon is used on a relatively lavish scale the question of cost is bound to arise. Welding argon was first sold in Great Britain at 1/10d per cubic foot, but its price has been gradually reduced and it now stands at about 7d per cubic foot. This in itself has made a considerable difference to the economics of inert-gas welding, but gas welding still remains very much cheaper when the cost of materials alone is considered. At present, however, it is the exception for gas costs to be a determining factor. There is an increased tendency for users to call for inert-gas welding—rightly or wrongly—because no danger of flux contamination arises, or perhaps because it is felt that weld quality will automatically be improved (in fact, a bad argonarc weld is just as likely to fail as any other).

The technical advantages of inert-gas welding which have just been considered are often an overriding consideration, and changes in design can make its use essential. Furthermore, there is the possibility of mechanising the newer processes, self-adjusting arc welding particularly, reducing gas cost to a negligible amount. All these tendencies increase the importance of technical and production factors and (combined with reductions in the price of argon) will broaden the field in which inert-gas welding can be used.

Finally, where finding the right method is concerned, metallic arc welding should be considered for structural and shipbuilding work. It is fast, does not involve the use of expensive and fragile equipment, and is easier to use outdoors. On the other hand, the weld quality is not as high and the electrode compositions are in practice limited to 5% and 10% silicon and to $1\frac{1}{4}$% manganese alloys. In the shop, self-adjusting arc welding will usually be the best technique, particularly if there is any prospect of mechanising the work, but for outside work the relative value of the two methods remains debatable. In Great Britain, the marine work which has been reported recently was carried out with self-adjusting arc equipment.[5, 6]

Jigs and Fixtures

It has already been pointed out that inert-gas-shielded welding demands more preparatory work than other methods, because the joint must be a good fit, and because good edge preparation combined with effective jigging can lead to big savings in production time. Wherever possible, edge preparation, which is necessary for material of $\frac{1}{4}$ in. and thicker, should be carried out by planing or routing, the latter method being particularly suited to aluminium. Chamfering the edge with a chipping hammer, which is good enough for gas welding, is not suitable for the newer processes. V-preparations should have an included angle of 90 deg. for argonarc welds and 70 deg. for the self-adjusting arc, with a root face of $\frac{1}{16}$ to $\frac{1}{8}$ in. Sections thicker than $\frac{3}{16}$ in. must be backed for single-pass welds from one side, using a grooved mild-steel bar or, as a cheap alternative, steel strip with a groove swaged down the middle. This groove must not be too shallow ; otherwise, the oxide film at the root face will not be dispersed and will be a serious cause of weakness. Alternatively, double-operator welding (Fig. 3) may be used. For this technique two welders work simultaneously from opposite sides of the joint, which is set up in the vertical position. Normally one welder feeds wire whilst the other controls penetration, and some skill is required in manipulation in order to disperse the oxide film at the butting edge. It is sometimes possible to avoid backing bars by designing the joint so that it comes over an external or internal stiffening member, or even by inserting an aluminium strip which remains in position after completion of the job. Both these methods are

Fig. 3. **Double-operator argonarc welding.** Distortion is greatly reduced, as compared with gas welding.

convenient for production, but make it difficult to inspect the weld either visually or by X-rays.

The use of jigs and fixtures for plate and sheet requires more care with aluminium than with steel. The amount of buckling caused by the welding heat is much greater than it is with steel, and when butt welds are made onto a backing bar, the sheet or plate tends to lift away from the bar, causing ugly and erratic penetration. There appear to be two reasons for this, i.e., the relative weakness of aluminium, which allows even thick sections to bend easily when compressed by expansion forces, and its high diffusivity and expansion coefficient. The theoretical work of Wells already referred to makes it possible to assess the amount of expansion under any given conditions. Figs. 4 and 5 show respectively the temperature distribution at right angles to the weld for the position of maximum temperature, and the corresponding amount of expansion between two fixed supports. The higher the value of $vd/4\alpha$, the less the expansion, which suggests that by increasing the speed buckling might be eliminated. Unfortunately, this does not appear to be the case. The highest measured value of $vd/4\alpha$ so far recorded for aluminium is 0·28 for a welding speed of 30 ipm, and this would reduce the amount of expansion, though not by a very substantial amount.[7]

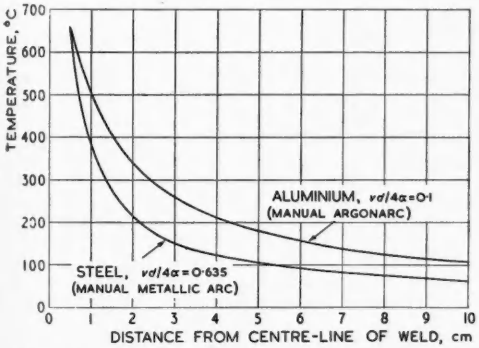

Fig. 4. **Temperature distribution at right angles to the weld for the position of maximum heat spread.**

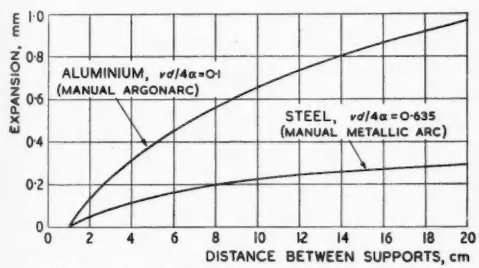

Fig. 5. **Expansion between two fixed supports.**

The craftsman welder overcame the effects of expansion by setting out his plates with a gap which tapered outwards from the start of the weld and in this way compensated for both local buckling and longitudinal contraction of the weld. It is difficult to set up a tapered gap in jigged work, however, and the only solution to the problem of longitudinal welds would seem to be the use of clamps which grip as close to the edge of the weld as possible. Circumferential welds in cylinders are, in principle, easy to jig since, if the backing ring is placed on the outside, the effect of expansion is to force the plates against the ring, thus making a perfect fit (Fig. 6).

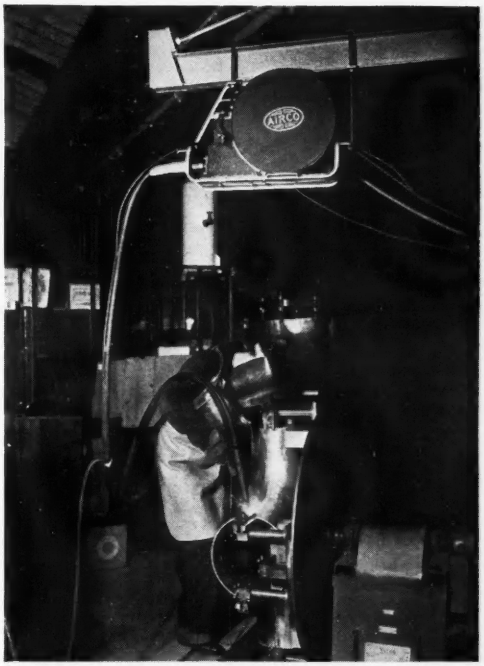

Fig. 6. **Welding of jigged work by the self-adjusting arc process.**
This is a good example of a joint which needs no top clamping, as expansion forces the plate into close contact with the backing bar.

The mechanical welding of aluminium is, as yet, very little developed in Great Britain, although automatic inert-gas metal arc equipment is now available for this purpose. Automatic argonarc welding has occasionally been reported, but the general use of this process for such work is limited by the difficulty of adding filler wire.

Weld Defects

Generally speaking, the inherent difficulties of welding aluminium are such that defects are more likely to occur than with, say, mild steel. Some have already been discussed. Oxide films and cracks are by far the most dangerous, the more so because both can be concealed below an apparently perfect weld bead. Tungsten inclusions are peculiar to argonarc welds and show up very easily on radiographs. Tungsten does not fuse into the weld bead and therefore causes a discontinuity; if large, it should be removed but, if small, it is unlikely to have any effect on weld properties. This defect occurs more frequently in welds made at high current in thick material, and to some extent its incidence may be affected by the type of electrode. Thoriated tungsten has a higher current capacity and will sometimes run with an unmelted tip but, when it does start to lose droplets, the rate of transfer is higher than with the pure metal. Zirconiated tungsten may well prove to be the best electrode for aluminium.

Flux inclusions in gas or metal arc welding may also be treated as discontinuities if they are totally enclosed by metal, but, if there is any possibility of flux being in contact with moisture from the atmosphere, corrosion will certainly take place.

Apart from the more difficult alloys, cracking will occur only in conditions of restraint, for example, where small patches are welded into plates, or in butt welds where the weld is heavily clamped. Cracking in butt welds may often be overcome by starting a few inches

from the edge and completing the unwelded portion last, whilst the patch-welding problem is solved by making the patch larger. Transverse cracks in butt welds may be due to the penetration bead fusing to the backing bar (in which case its origin is very obvious) or to an excessively wide bead. The heat-treatable alloys give rise to special problems and these materials should be welded only under the supervision of a welding engineer or metallurgist.

Recent Developments

The need to improve quality in the welding of thick plate for pressure vessels has been an important reason for the use of automatic processes in this field. This incentive is even stronger in the case of aluminium, where the chance of defects in manually welded plate thicker than ½ in. increases rapidly with thickness. Fortunately, automatic equipment of the inert-gas-shielded metal arc type is now obtainable in Great Britain. In one modification this machine differs fundamentally from the self-adjusting arc process in that heavier wires are used and the arc length is kept constant by a thyratron-controlled motor. This "controlled-arc" process is claimed to allow heavier deposits to be made and to give less trouble from porosity. If high-quality welds can be obtained in this way, the joining of thick plate will become much more practicable.

Although the inert-gas-shielded processes orginated in the United States, British investigators have been responsible for some interesting innovations. Some years ago the E.R.A., working in co-operation with B.W.R.A., developed an improved method of maintaining the a.c. arc for aluminium. Previously, a high-frequency spark had always been used to ensure re-ignition and, although this works in practice, it requires a transformer with relatively high open-circuit voltage (100-110 V) to ensure smooth operation. The surge injector causes a high-voltage pulse to be applied to the arc in phase with the welding current, and by using this better ordered process it is possible to reduce the open-circuit voltage, and therefore the cost, of the transformer.[8] Radio interference is also reduced. Commercial equipment incorporating a surge injector and series condenser is now available, so that the small shop can convert an existing a.c. transformer for argonarc welding at relatively low cost.

One of the disadvantages of self-adjusting arc welding used in conjunction with a normal d.c. welding machine is that, if the wire jams momentarily, the arc will burn back and fuse the wire to the copper guide tube; similarly, if it jumps forward the wire tip may fuse to the work. These "burn-backs" and "stick-ons" are a potent cause of delay in production, and various devices have been made to prevent them. The simplest is a relay which cuts out the welding current when the arc voltage is too high, i.e., when the arc is of abnormal length.

A more fundamental approach was developed by the General Electric Company in the U.S.A. and by E.R.A in Great Britain.[9, 10] A low open-circuit voltage machine (either transformer or rectifier) with a flat or slightly rising characteristic is used, the low open-circuit voltage causing the arc to extinguish before fusing to the contact tube, the flat characteristic giving a better degree of self-adjustment. The General Electric "Fillerarc" process incorporates both welding machine and a gun which pulls the wire instead of pushing it. Neither of these developments has yet been put on the market in Great Britain, despite the fact that it is a fairly simple matter to modify some d.c. generators to give the flat characteristic.

Quite recently, an American company has produced equipment to make tack and plug welds in aluminium, using a timer in conjunction with the self-adjusting arc process. This promises a wide range of application and it might even be practicable for spot welding aluminium and copper from one side.[11] The argonarc spot-welding gun cannot, unfortunately, be used for aluminium.

Stud welding of aluminium is now possible with standard equipment and has been used on a limited scale in ship superstructures. For the manufacture of cable sheathing the General Electric Company has applied "twin-arc" welding to the argonarc process. Two electrodes are enclosed in a single gas hood and connected to the secondary of a three- to two-phase transformer. Arcs strike between each electrode and the work alternately, and because of the broader distribution of heat a better weld profile is obtained than with a single arc. This improvement is obtained in welding tube without filler wire but so far there have been no reports of argon-shielded twin-arc welding for other types of production work.[12]

Finally, some mention should be made of pressure welding. Although this process has been thoroughly investigated by Tylecote, little practical use was made of it until the development of "cold welding."[13] It is by no means new, having been used for closing tooth-paste tubes, etc. for some time, but was given renewed life when applied to the fabrication of cable sheathing. The parts to be joined are carefully cleaned and pressed together, considerable reductions in thickness being required to obtain a sound weld. Lap joints can be made in small components by indenting them locally with a press tool, the indentations being spaced in the manner of spot welds. Cold welding is essentially a pressure-welding method, the modern version, quicker but less certain, of the hammer welding process which died out so many years ago.

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Joining Aluminium by Soft Soldering

By H. C. Watkins, A.I.M.*

Soft soldering may be defined as a process for the joining of metals at relatively low temperature by the use of filler alloys which wet the joint members, flow between the surfaces to be joined, and adhere strongly to them on solidification. Wetting of the joint surfaces can occur only when the liquid and solid surfaces are free from oxide films, this condition being normally ensured by the use of suitable fluxes. Metals such as copper, copper-base alloys, mild steel, tinplate, and electroplated finishes, including silver, cadmium, and nickel, are readily soldered. With aluminium and the light alloys, however, soft soldering is by no means well established as a jointing method, in spite of the fact that there are many applications and potential applications where the use of a soft-soldering technique would greatly facilitate assembly. Although solder and flux compositions and procedures for soldering aluminium were proposed even before Hall and Héroult made their discoveries, progress in this method of joining aluminium has been retarded, primarily because of two factors, i.e., the difficulty of removing the tenacious oxide film, and the liability of the soldered joints to fail as the result of electrolytic corrosion.

Soldering Techniques

Methods of tinning and soldering aluminium fall into two classes, i.e., those in which the oxide film is removed mechanically, and those in which it is removed chemically. A feature of nearly all methods is the general need to pre-tin the surfaces to be soldered before assembly of the joints, unless capillary penetration is required on only a very limited scale. When a flux is used, it is sometimes sufficient to pre-tin one surface; alternatively, the solder, in the form of a shim or washer, may be pre-placed in the joint. Pre-tinned aluminium should be soldered as soon as possible after preparation, as ease of soldering decreases during storage.

Mechanical Removal of Oxide :—

Mechanical methods of oxide removal have for some time been practised with good results for certain types of jointing. With the heavier gauges of material, the oxide is removed from the areas to be soldered with a file, the filed surfaces are heated until a stick of solder just melts on contact, and are then tinned by rubbing with the solder stick. Even tinning is obtained by vigorous scratching through the molten solder layer with a steel wire brush.

In order to increase the abrasive action resulting from the rubbing of a stick of solder over a heated aluminium surface, it has been proposed[1] to incorporate into the solder a finely divided abrasive, such as carborundum, in the form, for example of a core in a stick or wire. Claims have also been made[2] that the presence in the solder of hard metallic crystals with a high melting point will serve a similar purpose as an added non-metallic abrasive.

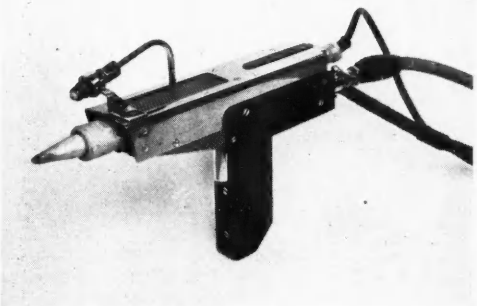

Fig. 1. **Ultrasonic soldering iron with gas-jet attachment.**

To obtain satisfactory tinning with light-gauge bright-rolled aluminium strip or sheet, it is often sufficient merely to rub the area to be soldered with the tip of a well-tinned soldering iron.

The application of abrasive methods of soldering has been limited, owing to the rather slow and laborious nature of the process, apart from the danger of damaging the work being soldered. These objections were largely overcome by the introduction into Great Britain a few years ago of the ultrasonic soldering technique. The effectiveness of ultrasonic tinning is considered to be due to cavitation erosion, to which both aluminium and its natural oxide film are very susceptible. The oxide film is disrupted by forces of high magnitude developed at the work surface, permitting tinning of the exposed aluminium before re-oxidation can occur.

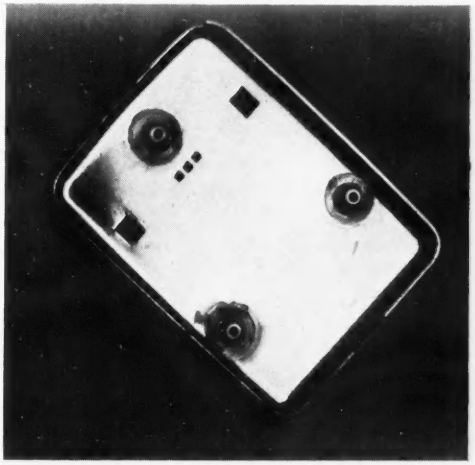

Fig. 2. **Studs of A1-Mg-Si alloy soldered to A1-Mg alloy pressing, using ultrasonic soldering technique.**
(Courtesy of Amplivox Ltd.).

In the ultrasonic soldering equipment manufactured by Mullard Ltd., the soldering iron consists essentially of an electrically heated soldering bit which is vibrated at a frequency of approximately 20 kc/s by means of a magnetostrictive transducer. The tip of the bit is tinned with solder and then held in contact with the surface to be soldered, additional solder being fed from a stick or wire, as required. Local tinning of light-gauge aluminium sheet is readily obtained in this manner, but care must be taken when dealing with fine wire and foil, since the erosion produced may be sufficiently severe to cause disintegration before uniform tinning is secured. An earlier limitation of the ultrasonic soldering iron, i.e., its inability to develop sufficient heat to tin and solder heavier workpieces, has now been overcome by the provision of a built-on gas torch for preheating (Fig. 1). With this attachment the iron can be used successfully for the repair of cracked castings, for the solder-filling of seam welds in aluminium car-body stock, etc.

Available from Pantak Limited, of Slough, is a similar type of ultrasonic soldering equipment, manufactured by Siemens-Schuckert in Germany. Built into

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the soldering head, which is connected to the high-frequency generator by a flex, is the soldering bit. This bit is constructed of magnetostrictive material, which converts the high-frequency oscillations (20 kc/s) into mechanical oscillations with amplitudes of approximately 0·001 mm.

Small items and wire ends are more easily tinned by dipping into a solder bath having a magnetostrictive transducer attached to the base. Fig. 2 shows a small aluminium-alloy pressing, to which three studs have been soldered, the pressing having been pre-tinned locally by means of an ultrasonic iron and the studs by dipping in an ultrasonic bath. The pressing was subsequently anodised and dyed, the soldered joints being protected from the anodising solution by means of rubber gaskets.

The application of ultrasonic dip-soldering has been restricted by the fact that for efficient operation on larger workpieces it is necessary to incorporate large and expensive transducers. In order to overcome this drawback, it has been proposed[3] to employ an immersible type of ultrasonic soldering iron, the bit of which is provided with an aperture. The work to be tinned, e.g., wire or strip, is passed through the aperture in the bit, which is immersed in a bath of solder.

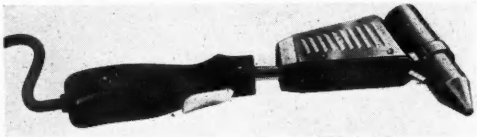

Fig. 3. **Aluminium soldering tool with vibrating brush.**

A new electrically heated aluminium soldering tool (Fig. 3), manufactured by the Belark Tool & Stamping Co. Ltd., is provided with a small steel wire brush, located in the copper bit, which can be vibrated at a frequency of 100 cps. The bit is allowed to reach the working temperature, and is then held square to the surface, so that the wire brush is in contact with the metal. A small pool of solder is formed around the bit, the wire brush caused to vibrate, and the tool moved over the area to be tinned. As soon as the oxide film is disrupted, the molten solder tins the surface, which can afterwards be soldered by normal methods.

When employing the techniques outlined above, it is sometimes found that joints of poor mechanical strength are obtained after sweating together the tinned surfaces. It would appear that oxide films present on these surfaces prevent uniform adhesion. In suitable cases the parts being soldered are moved relative to one another whilst the solder is still fully molten, excellent adhesion being secured.

Chemical Removal of Oxide :—

Three types of flux for use in the soldering of aluminium are at present available, and each has a useful field of application, depending on the work.

The oldest fluxes are mixtures of heavy metal chlorides, such as those of zinc, cadmium, and tin, sometimes with additions of alkali metal and ammonium halides. These fluxes react when heated on an aluminium surface to form volatile aluminium chloride and deposit a thin layer of heavy metal, which tins the aluminium. A flux of this type, consisting of a mixture or double salt of anhydrous stannous chloride and ammonium chloride, may be applied to the areas to be soldered in powder form, soldering then being carried out in the usual manner by the application of heat and solder, or used in the molten state for dip-soldering purposes. In the latter case the flux is maintained at 230° to 260° C, the work being dipped into solder immediately after removing it from the flux. It has also been proposed[4] to provide a cored solder incorporating this and similar fluxes for use in hand-soldering operations. Owing to their high temperature of operation, the objectionable smoke evolved during heating, and the danger of subsequent corrosion arising from the presence of unheated salts in the joints, these reaction-type fluxes do not find wide application.

Fluxes which resemble those just described, in that they deposit a layer of heavy metal when heated in contact with an aluminium surface, but which are largely free from their disadvantages, are marketed by I.C.I. Ltd. These fluxes, in the form of viscous liquids, consist essentially of fluoborates of aliphatic polyamines, amino-alcohols, ammonia, and metals such as cadmium dissolved in an excess of an aliphatic amine, an example of such a flux having the following composition :— Ammonium fluoborate 8·6%, cadmium fluoborate 5·0%, triethanolamine 86·4%[5]. Application of these fluxes is as in conventional soldering operations, heating being by torch, soldering iron, or hot-plate. Excessive heating must be avoided, since rapid charring of the organic base occurs at temperatures of about 300° to 350° C, rendering the flux ineffective. The solder used should be fully liquid at a temperature below 275° C and direct flame heating of the flux must be avoided. When a soldering iron is used, frequent cleaning of the bit will be found necessary, owing to the accumulation of carbonised material. It is not essential to remove the flux residue remaining after soldering, but removal by water washing (followed by careful drying) is desirable, since the joints, unless completely sealed off from the atmosphere or exposed under very dry conditions, must be given a protective coating.

Rosin-based fluxes for use in the soft soldering of aluminium have been introduced recently by Enthoven Solders Ltd. These fluxes, which are being made available in liquid and paste form, as well as in a cored solder wire, are intended primarily for use in the electrical and electronic industries. As in the case of other rosin-base fluxes, they are suitable only for comparatively light soldering operations, where the work can be raised rapidly to the soldering temperature. Figs. 4 and 5 are illustrative of possible applications. Where the parts to be soldered are dirty, cleaning in a weak, hot alkaline solution (e.g., 5% trisodium phosphate solution) is advisable. When dip-tinning, using the liquid flux, it is sometimes found advantageous to preheat the work by immersion in the solder before fluxing. The residues from these fluxes are hard and non-corrosive.

Mention should also be made of fluxes for aluminium containing as active agents compounds of hydrazine or hydrazine derivatives. Such fluxes are not yet available

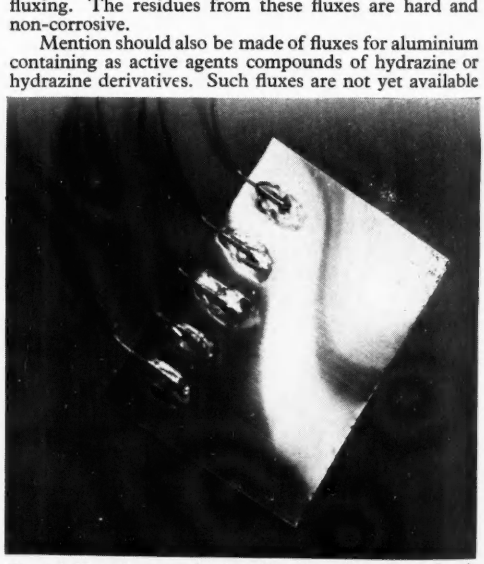

Fig. 4. **Tinned copper leads soldered to thin sheet aluminium, using rosin-based cored solder.**

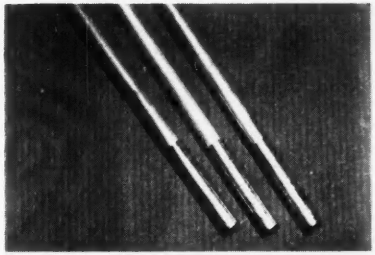

Fig. 5. **Al-Mn alloy tubes dip-tinned, using liquid rosin-based flux.**

in Great Britain, although it is understood that extensive tests are being made in the U.S.A. with assemblies soldered with these fluxes. One flux, but not necessarily similar to those being tested[6], has the following composition:—Stannous chloride 50 to 90%, zinc hydrazinium chloride 5 to 30%, and hydrazine monohydrohalide 5 to 30%.

Composition of Solder

Conventional tin-lead and antimonial tin-lead solders do not wet aluminium very readily, and joints made with them rapidly lose their strength when exposed to moist air. Zinc, which is appreciably soluble in solid aluminium, has good wetting properties and is the best solder for aluminium insofar as resistance to corrosion is concerned. It has the disadvantage, however, of a melting point (419° C) which exceeds even that of the lead-silver eutectic used, for example, for high-temperature soft-soldering of copper, by more than 100° C. Additions to zinc of metals with lower melting points, such as tin and cadmium, yield lower melting solders, but at the same time have an adverse effect on the corrosion resistance of the joints. Dowd[7] has considered the mechanism of the corrosion of soft soldered joints in some detail. Failure occurs in the interfacial layer formed between aluminium and the solder as the result of diffusion during soldering. The interfacial layer corrodes preferentially because of its higher potential compared with aluminium and the metals commonly used in solder, with the exception of zinc, the corrosion products prying the joints apart.

The solders for aluminium available commercially are either zinc-base, often containing up to 5% aluminium (M.P. 382° C) or a few percent of silver; tin-base with additions of zinc or cadmium, or both; or tin-lead alloys with additions of zinc and sometimes also of cadmium. A hard solder for aluminium, applied with a torch at temperatures of 450 to 500° C, is available from the Sheffield Smelting Co. Ltd.

The application of the zinc-base solders is limited by their high melting points and the fact that the use of chloride fluxes, the residues from which must be completely removed to prevent subsequent corrosion of the aluminium, is necessary. Joints made in these alloys have a long life, even under severe atmospheric conditions. The soft solders, such as the tin-zinc alloys containing 10% zinc (M.P. 210° C) or 20% zinc (M.P. 267° C), have a wider range of application, since they can be used with organic-base fluxes and can be applied at temperatures at which there is considerably less danger of heat damage to the parts being soldered. The joints made with these solders must, however, normally be protected by means of a coating of paint or varnish, or by some other moisture-excluding material. The rate of failure of unprotected soft soldered joints in aluminium depends on solder composition, joint design, and the environment to which the joints are exposed. Generally speaking, the higher the zinc content, the longer the corrosion path, and the drier the atmosphere, the longer will be the life of the joint. Lap-, scarf-, or sleeve-type joints are to be preferred; butt joints should be avoided. A well-made joint exhibits neat solder fillets which enhance its strength. Joint strengths average 2·5 to 5·0 tsi, according to the composition of the solder, the thickness and temper of the aluminium, and the joint design.

Base-Alloy Composition

Wrought-aluminium products are usually more readily soldered than castings. The easiest to solder are super-pure and commercially pure aluminium and the aluminium-manganese alloys, such as D.T.D.213.A, especially when these are available in the bright-rolled condition. Both magnesium and silicon reduce the solderability of aluminium, while alloys containing more than about 1% magnesium cannot be soldered satisfactorily with the use of organic-type fluxes. Another factor to be borne in mind when considering the suitability of an aluminium alloy for soft-soldering purposes is the possibility of embrittlement resulting from the penetration of solder into the grain boundaries. Investigation has shown[8] that this is particularly liable to occur when severely stressed magnesium-containing alloys are soldered with tin-zinc solders. Cold-worked, fully heat-treated aluminium-magnesium-silicon, and fully heat-treated aluminium-magnesium-zinc alloys were found to be especially susceptible to this type of failure. The aluminium-magnesium alloys N.S.4 and 5, when annealed, are free from any tendency to this defect. Pure aluminium and aluminium-manganese alloys in any temper are not subject to solder penetration. Zinc-base solders have not been found to give rise to embrittlement, possibly owing to the annealing of work-hardened material in the vicinity of the joints, resulting from the higher application temperature of these alloys.

Clad forms of the strong aluminium alloys can be soldered as readily as pure aluminium but, unless care is taken, molten solder may penetrate the core at sheared edges.

The ease of soldering aluminium may be improved by the application of an electroplated coating. Nickel has been preferred for this purpose, because the coating thickness required is relatively small (about 0·00005 in.), but copper, cadmium, or tin can also be used. Nickel is plated from a sodium sulphate type of nickel solution, following a special preparation of the aluminium surface to ensure good adhesion of the electro-deposit[9]. Such electroplated aluminium can be soldered to itself and to other metals and alloys with the use of conventional solders and fluxes. Nickel coatings on aluminium produced by an electroless method[10] are also stated to provide a satisfactory base for soft soldering. Attempts to provide a readily soldered surface on aluminium by immersion tinning processes have not been successful.

Applications of Aluminium Soldering

It is to be expected that the soft soldering of aluminium will continue on a restricted scale as long as uncertainty exists regarding the eventual life of the joints. Several effective fluxes are available, and it is reasonable to suppose that improvements will be made in the future to extend the usefulness of these materials. With regard to improvement in the solder alloys which fall properly into the soft-solder range, i.e., those with melting points not exceeding about 300° C, there is less cause for optimism. It is true that numerous claims[11] have been made for tin- and lead-base solders, in which improvements in both wettability and corrosion resistance of the joints have been obtained by means of minor alloying elements. Whilst the life of a joint may be prolonged in this way, some form of protection for the joint is still necessary in order to avoid eventual failure. Where it is possible to provide such protection, the soft-soldering process may be used with confidence. The present high price of copper has stimulated interest in the possible substitution of aluminium or aluminium

alloy, particularly in the electrical and heat-exchanger industries, and it is to be anticipated that greater use will be made of soft soldering, where suitable protective coatings can be employed. Already there are several well-established uses of the soft soldering process for the jointing of aluminium, three instances of which are as follows :—

(1) *Aluminium Cable Sheathing* :—

Wiped joints of the lead or copper sleeve type are readily made in aluminium sheathed cable by a simple and easily acquired technique. The ends of the sheath are first cleaned with trichlorethylene and are then abraded evenly with a clean medium-cut file to remove the existing oxide film. The sheathing is next heated with a blow-lamp until a stick of 90/10 tin-zinc solder will just melt when rubbed on the surface. Rubbing of the solder stick is now continued with a longitudinal motion until an even film is obtained over the whole of the joint area, the blow-lamp flame being removed during the tinning operation (Fig. 6). Whilst the

Fig. 6. **Aluminium plumbing : Tinning prepared sheath.**
(Courtesy of British Insulated Callender's Construction Co. Ltd.).

tinned layer is still molten, it is brushed circumferentially with a clean file card to remove the oxide formed after filing, after which the sheathing is re-heated and the application of solder repeated. The plumb is completed in the usual manner but without the use of tallow. The wiping solder should be non-antimonial, B.S. Grade "J" plumbers' metal (30/70 tin-lead) being suitable for this purpose. It is important not to overheat the sheathing during soldering, the temperature required being about 250° C. The joint is finished by applying bitumen paint and protective tapes over the exposed sheath and plumb.

This procedure has been thoroughly tested and has been used satisfactorily in a large number of cable installations.

(2) *Aluminium-Cored Cables* :—

The majority of copper conductors for power cables are jointed and terminated by means of soldered ferrules. A similar technique can be used with aluminium conductors, provided that an appropriate flux and solder are employed, and that each layer of strands is exposed directly to the action of the flux and the solder metal.

The first step in making a joint is to cut back the layers of strands in steps, so that each layer is exposed over a sufficient length for satisfactory tinning to be obtained. The centre wires are then splayed out to a diameter not exceeding the overall diameter of the conductor. After cleaning the exposed wires with trichlorethylene, a flux based on triethanolamine is brushed vigorously into the strand interstices. The conductors are now tinned by pouring molten solder (usually a lead-base alloy containing approximately 31% tin, 8% zinc, and 8% cadmium), heated to from 345° to 370° C, over the exposed strands, alternate applications of flux and solder being made as necessary until tinning is complete. After the last application of metal, excess solder is rapidly wiped off with a clean, dry cloth. The weak-back ferrule, pre-heated by immersion in the solder pot, is fitted centrally over the joint with the opening on top. Solder is then poured over the assembly and, when fully hot, the ferrule is closed up tightly with pliers, additional solder being poured into the slot as the solder contracts on cooling.

(3) *Aluminium-Foil Capacitors* :—

Several methods have been used or proposed for pre-tinning the ends of aluminium-foil capacitors prior to soldering on tinned copper wire leads.

A method which has been practised both in Great Britain and in the U.S.A. consists of pressing the foil ends against the tinned surface of a drum rotating slowly in a bath of tin-zinc solder maintained at about 400° C. The oxide film is removed from the aluminium by abrasion, and the cleaned surface is wetted immediately by the solder. Leads can be soldered to the pre-tinned aluminium surfaces, using conventional rosin-cored solders.

An objection to this technique is that a considerable quantity of wet dross is formed on the solder bath, arising from the rotation of the drum in the solder. This dross, which forms a pasty layer at the surface of the solder, must be removed from time to time and represents an appreciable solder loss. A similar method, not involving, however, the use of a solder bath, has been proposed[12], in which the foil ends of capacitors are pressed against and drawn across the solder-coated surface of an aluminium block which is heated to a temperature just above the melting point of the solder used, or pressed against the tinned aluminium face of a rotating wheel.

Apart from the procedures involving abrasion outlined above, it is possible to pre-tin and solder aluminium-foil capacitors successfully with the special rosin-cored solder referred to earlier.

The author wishes to thank the Directors of H. J. Enthoven & Sons Ltd. for permission to publish this paper.

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The Metallurgical Control of High-Quality Aluminium Forgings

By T. E. Murch.*

With the advent of the gas turbine and its application to aircraft designed for speeds around or above the speed of sound, components are being stressed to higher levels than ever before, making it increasingly imperative that the materials utilized both in engines and airframes should be not only light and strong but should have high resistance to fatigue and be capable of giving many hundreds of hours of service with the utmost reliability. Such a combination of properties is best obtained with wrought materials, and the complexity of components required for modern aircraft purposes necessitates the use of drop forging or pressing for their production. Even for prototype work, it is common for components to be machined from forged blanks which have been specially produced and held in stock at the aircraft works.

Production of both the forged blanks and the stampings is a highly specialized business, involving during manufacture very careful control at all stages, which themselves are the subject of continuous development and improvement. The experience gained and the specialized methods thus evolved become available to the user of forgings for general engineering purposes, although his inspection requirements may not be so exacting.

This article outlines some of the methods whereby the light-alloy forging industry endeavours to ensure that the increasingly exacting requirements of the aircraft industry are maintained.

Inspection

The quality of aluminium alloy forgings depends to an important extent upon the quality of the original cast ingots from which they are made. Such ingots must be quite sound, with no inclusions, segregations, cavities, or cracks, and should have a fine, even grain structure.

The metallurgical control of aircraft forging starts, therefore, with the most rigorous inspection of the ingots, to ensure that they are quite free from defects, and proceeds through every stage of manufacture—extrusion, forging of dummies, drop forging or die pressing, and heat treatment.

Cast Billets and Forging Stock :—

Practically all forgings are produced from semi-continuously cast billets, either by direct manipulation of the cast billet or through an intermediate extrusion operation, and a large amount of deformation is required to produce a fine grain size and a closely controlled grain flow, in order that the component may develop the highest possible mechanical properties in the directions and localities at which the highest stresses will be imposed in service.

The cast billets used for these purposes are normally inspected by the established methods of taking sample slices at selected locations and subjecting them to close examination after polishing and etching. Such methods of examination, however, are effective only on a quality-control basis and it has now become essential to carry out additional non-destructive examination of each individual billet. Such non-destructive testing has been made possible by the development of ultrasonic flaw detectors, which are now in use by every major aluminium company.

Ultrasonic Flaw Detectors :—

With ultrasonic flaw detectors, not only is it possible to detect the presence of a flaw but experienced operators can determine the position and size of the defect and can also interpret its classification. It will therefore be seen that intelligent use of these instruments, which have now been brought to a high degree of efficiency and portability, can materially assist in the elimination of internal defects, not only in cast billets but also in extruded forging stocks, and indeed in the forgings themselves. This latter application at present is limited to fairly large hand forgings of regular shape, but a close degree of control can be maintained for stampings and pressings by prior examination of the stock.

Forgings :—

With very large forgings, it is normal for considerable machining allowances to be left on all surfaces, and this simplifies the problem of inspection for surface defects. On the other hand, large numbers of the smaller drop forgings and pressings are produced to finished size without machining allowance over a considerable proportion of their surface area. The production of such forgings raises special problems in manufacturing processes, handling, and inspection in order to eliminate the slightest scratch or surface defect, which might become a stress raiser from which a fatigue crack might initiate.

To meet this demand, extraordinary measures are undertaken, involving the use of specially prepared forging stock, the production of dies with completely smooth working surfaces, and carefully planned procedures at every stage of manufacture, to ensure that exposed surfaces of the forgings are not damaged in any way. All transport between operations is carried out in special containers and the work is closely inspected between the stages. Any defects discovered are removed by milling or scuffing, and the parts are subsequently re-inspected after etching. Only when the inspectors are satisfied that the components are free from surface blemishes do they go on to the next operation.

Polishing Prior to Final Inspection :—

Before the final inspection stage, this type of component is often hand-polished all over to a degree approaching a mirror finish, special care being taken to avoid plastic flow in the material immediately adjacent to the surface, since such flow merely hides defects instead of revealing them. Hand polishing to this degree is necessarily an expensive and time-consuming process, and in some instances it has been possible to use alternative methods, such as electro-polishing and Roto-finishing. While electro-polishing is normally confined to the inspection of blades for gas turbines, Roto-finishing is frequently used on larger components up to 10 lb in weight. It consists of a barrelling process in which forgings are rotated in a mixture of limestone chips, detergent, abrasive compound, and water. It is a two-stage process, requiring initial polishing followed by honing, and it is possible to obtain surface finishes down to 10 micro-inches without difficulty at a far faster rate than can be achieved by hand polishing. This process is also being used currently to polish a variety of general engineering components which had previously required hand polishing.

Anodising :—

Whichever method of surface preparation is used, the polishing operation is followed by anodising in chromic acid, after which the work is dipped in running water and allowed to stand for at least 24 hours, before final inspection. Components so processed may be inspected to the ultimate degree, since any open cracks or folds are normally shown by seepage of the chromic acid, whilst closed hair-line defects are shown by an optical effect as a dark line against the polished background (Fig. 1). After initial final inspection, minor faults so detected may be removed by filing, scraping, or gouging (Fig. 2), followed by blending of the edges of such incisions as may be made to prevent the occurrence

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Fig. 1. **Polished and anodised drop forging.** The surface defects revealed are delineated by pencilled rings. (Courtesy of The de Havilland Aircraft Company.)

of notch effects and stress raisers which might in themselves lead to fatigue failures. Thereafter, the areas affected may be inspected after treatment with a special etching agent applied locally or, if necessary, the whole component may be stripped and re-anodised before further inspection.

Especially rigorous inspection is usually applied to hydraulic components which are subjected to high internal pressures in service and which are frequently machined in such a way as to leave only a thin ring of metal adjacent to the outer surface of the original forging. In these circumstances, not only is it essential that there should not be the slightest defect on the surface of the material but it is also imperative that the material at and adjacent to the surface should be of the finest possible grain size, particularly in the vicinity of the flash-line. Any tendency to coarse grain in such components might lead to the position whereby a thin wall needing to withstand a high pressure might consist of only a very few large grains without the ability to resist deformation and fracture. In order to prevent such an occurrence, it is necessary that the stock used for the manufacture of such components should be very heavily worked before the final stamping operation and to make quite sure that the manufacturing process has resulted in a suitably fine grain structure by taking components out of production on a quality basis for macro-examination of the important areas in the component. This is done in co-operation with the customer, who marks on his drawing the areas of the component where the finest grain is essential.

Liaison

The light-alloy forging industry has long maintained a very close liaison with its customers in the aircraft industry, to ensure that the designers of components in light alloys are familiar with the forging characteristics of the materials concerned and are able to take full advantage of the properties of the alloys, while avoiding design details which might lead to difficulties in the production of the components. It is customary for designers to draw up their initial requirements, indicating the type of grain flow they would like and stating the minimum mechanical properties desired, both in the longitudinal and transverse directions in the more highly stressed localities. The preliminary drawings are examined by the forgers' representatives and, if the design of the component is thought to be unduly difficult to manufacture or if it is felt that the mechanical properties required in any particular direction could not be achieved, the matter is discussed in detail and an agreed compromise is usually forthcoming. The final drawing is then prepared, showing the grain flow and minimum mechanical properties forecast by the forger. In all such cases the forger prepares a number of sample components, which are cut up to prove the mechanical properties and the direction of grain flow, as indicated on the drawing. Should these checks show that the component does not meet all the requirements, then further samples are produced, using a modified method of manufacture, and the process is repeated until the grain flow and mechanical properties of the sample components are in accordance with the agreed requirements.

At this stage a report is made of the results of the cut-up tests and macro-examination and copies of these are sent to the customer, together with the actual macro-sections and a fully heat-treated sample, in order that the customer can take his own cut-up tests if he so desires. On approval of such sample reports, bulk production proceeds according to the orders, and further stampings are taken out of production at regular intervals and are cut up in a similar manner to the original sample stamping. The results obtained on these check tests are correlated against those shown in the original report, and this constitutes a constant check, ensuring the continuity of the approved method of manufacture.

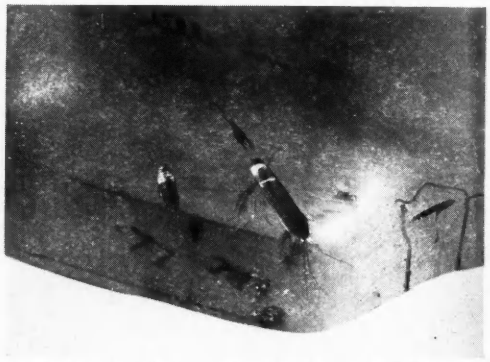

Fig. 2. **Portion of drop forging, showing method of gouging applied to reveal the depth of defects.** (Courtesy of The de Havilland Aircraft Company.)

Some Lines of Development

As already mentioned, the requirements of high-speed aircraft are growing more and more severe ; it is therefore necessary to maintain constant research and experimental work, with a view to improving both the materials and the products. At the moment, much attention is being paid to the possibilities of improving the resistance of high-strength materials to stress cracking by a study of the effects of the addition of chromium and manganese. The question of internal stress is also being studied very closely, since it is known that the lower the internal stress in any particular component the greater will be its chances of long life in service. To keep internal stresses low, it is often necessary to quench the material in very hot or boiling water, but such quenching may yield lower mechanical properties when chromium is present in the material. Since there appear to be definite advantages in the inclusion of chromium, much research is being carried out to discover methods and compositions whereby the advantages of chromium additions may be made without the pitfalls found with their use.

As a result of the high internal stress which can occur when large and complex components are quenched in water at temperatures below the boiling point, it is becoming increasingly necessary to deliver the components in the " as-forged " or in the annealed condition for rough machining by the customer before heat treatment at the forger's works. Treatment of this kind

(*Concluded on page* 243)

Die Casting in Aluminium

By Frank G. Woollard, M.I.Mech.E., M.I.Prod.E., M.I.I.A., M.S.A.E.

Die casting, whether by the gravity or the pressure process, is relatively new in the metal-working art. It is true that gravity die casting was used in the middle ages for the production of pewter ware, but it was Cothias, in Paris, who made the first practicable aluminium die castings for engineering purposes. This was in 1909 and the process was taken up in Great Britain in 1912. The pressure die-casting process, which had its origin in type-founding, *circa* 1850, did not become an engineering possibility until 1915, when the Doehler Die Casting Co. of America produced the first commercial pressure die castings in aluminium alloy.

Although these processes are less than fifty years old, they have made enormous strides. Indeed, in the mass-production industries, insofar as light metals are concerned, they threaten the very existence of the classical sand-casting method. The latest trends in this field indicate that the sand process is dropping in volume and that gravity, which gained considerably at the expense of sand, is now holding its own, since the losses to the pressure process are offset bv the further gains from sand. Meanwhile, the pressure process is showing a very marked increase in volume, particularly notable during the past two years.

Gravity or permanent-mould die casting can be carried out in cast iron and the alloys of aluminium, copper, lead, magnesium, and tin. In volume the aluminium alloys predominate. Pressure die castings can be produced in the alloys of aluminium, copper, lead, magnesium, tin, and zinc. The aluminium and zinc alloys predominate, the volume, owing to the weight factor, being very nearly equal.

There is less competition among the various alloys than might be expected. Each fills a need and they are, as a rule, chosen for their particular characteristics, but naturally the state of the metal market has also some influence on the choice of alloy. Aluminium has the specific advantages of light weight, certain valuable thermal properties—very important for automobile and aircraft components—and excellent mechanical characteristics at low temperatures. Moreover, if the right alloy is chosen, aluminium is highly resistant to corrosion and the aluminium-magnesium series is well suited for marine applications.

Advantages of Gravity Die Casting

For small lots and for very complicated castings, particularly when these are on the large side, the sand process still remains supreme ; however, when quantities are reasonably large, the gravity process can show the following advantages :—

(1) Gravity castings are generally cheaper than sand castings, where the quantities justify the cost of the dies.
(2) The castings require less machining, because the dimensional tolerances are much closer.
(3) There is, in consequence, much less metal to cut to waste.
(4) The liability to porosity is considerably reduced.
(5) The mechanical properties are considerably improved.
(6) The process is cleaner and does not involve the disposal of large quantities of waste material.

It is true that the cost of dies will be at least twice that of metal patterns, but this is offset by the greater rate of production and the lower labour costs involved.

Advantages of Pressure Die Casting

To the benefits derived from gravity die casting the pressure die-casting process can add the following :—

(7) A production rate greatly above that of the gravity process.
(8) Greater precision in the details of the product.
(9) An ability to produce tapping holes and, when necessary, integrally cast rivets.
(10) An ability to reproduce, clearly and sharply, reference numbers, instructions, etc. in relief or intaglio.
(11) The possibility of avoiding machining on all parts where close limits are not essential.

The cost of dies for pressure casting would be more than double that for gravity dies but, here again, this is compensated by higher output and a superior surface finish. The choice therefore between the processes is governed by economics, in which the quantity of articles required is most frequently the deciding factor. Nevertheless, in certain cases, where very complicated components are required, it has been found that pressure die castings are an economy, even though the numbers required are so small that, *prima facie*, there appears to be no justification for the more expensive process.

Maximum Sizes of Die Castings

With regard to size, there is virtually no limit to the size of gravity die castings, provided that the casting can be designed so that there will be no undue stress set up on cooling and that the die can be opened and the casting extracted without tearing the metal. With pressure die castings, the limit reached in Great Britain is 300 sq in. projected area at the die joint by 10 in. deep, with a weight of 10 lb. There are indications that in the U.S.A. these dimensions have been exceeded and castings of 17 lb in weight, but including the runner, have been reported. Recently, the Doehler-Jarvis Corporation has built a giant machine—the largest in the world—intended for the production of aluminium cylinder blocks cast in one piece. These castings will weigh 75 lb, and the production rate is estimated at 30 to 40 pieces per hour. This machine weighs some 35 tons and cost about $150,000. This is a most interesting project, since it indicates great faith in both the future of aluminium and in the die-casting process.

Specialist Die Casters

In the United Kingdom most aluminium castings are supplied by specialist foundries, although there are end-product concerns who make the majority of their own castings and only call on the jobbing foundries for balancing quantities. The supply foundries of the larger sort employ specialists who can advise purchasers both with regard to the correct alloys to use and to the detail design of the components submitted to them. Since they have a vast experience of many different trades, their advice is of considerable value and should, when possible, be followed. By so doing, scrap in the foundry will be avoided and wastage, due to the machining of parts later found to be faulty, obviated.

It is important that the supplier should be consulted while the design is still fluid, so that alterations can be made without upsetting the balance of the design. It will usually be found that these amendments to the design will not adversely affect the finished article, but the economies made by following this specialist advice can be quite considerable.

Choice of Alloys for Gravity Die Castings

With respect to the choice of alloys, there is a wide range for both the gravity and pressure processes. It is advisable to use specification alloys, as these have been framed to give the best to suit specific purposes. For gravity die castings some fourteen specification alloys are listed in Great Britain under L.M. designations—see B.S. 1490—with some variants for heat treatment. Two of these alloys, L.M. 13 and L.M. 14, are mainly

used for pistons. They have a low thermal expansion and maintain high rigidity at elevated temperatures.

L.M. 1 can be regarded mainly as a space-filler and L.M. 4 as one of the most useful general-purpose alloys, capable of withstanding moderate stress and shock and holding hydraulic pressure.

L.M. 5 is an interesting sea-resisting alloy of the Birmabright series, combining rigidity with shock resistance, and is largely used in marine applications.

L.M. 6, which is very fluid in the molten state, is suitable for complex castings of very thin section and for moderately stressed parts which are subject to light shock. This is one of the Alpax series. L.M. 9, another in this series, is suitable for stressed castings which are not subject to shock.

L.M. 10 is a remarkable alloy which combines high proof stress and high ultimate strength with an unusually high elongation. This alloy, which needs rather special care in the foundry to obtain the best results, is particularly suited to components which are highly stressed and where shock loading prevails; by virtue of its purity it is also very resistant to corrosion. L.M. 11 combines high strength, ductility, and high shock resistance, but also requires special foundry technique to ensure its extremely good mechanical properties.

L.M. 20 is a general-purpose alloy of the L.M. 6 type, but with somewhat lower corrosion resistance, while L.M. 8 is an alloy in the magnesium-silicon series; it enjoys a wide range of mechanical properties, according to the heat treatment given. This alloy is very resistant to atmospheric conditions, including coastal exposure. At running temperature this metal is unusually fluid, thus producing sound castings in even the most complicated components.

L.M. 22 is a special edition of L.M. 4, with the elements very much more closely controlled. It has good foundry characteristics and chill-cast specimens rate high. It has high mechanical stability and is suitable for parts subjected to heavy duty.

Choice of Alloys for Pressure Die Castings

Pressure die-casting alloy specifications are not as numerous as those for gravity die castings, and there appears to be a tendency to curtail them, since their properties in many cases are similar. There are in all six specifications current in the United Kingdom. The mechanical tests are made on pressure-cast bars of ¼ in. diameter, instead of the 0·564 in. diameter chill-cast bars used for gravity die tests.

L.M. 2 and L.M. 4 are useful and popular alloys, L.M. 2 being a general-purpose alloy used for moderately stressed castings. L.M. 5, the alloy in the Birmabright series, is most useful for marine and other applications where resistance to corrosion is important. L.M. 6, with properties which parallel those of L.M. 4, is popular and so is L.M. 20, which is again similar. L.M. 24 is a newcomer to the specification alloys and is gaining in favour.

Apparatus for Gravity Die Casting

Gravity die-casting apparatus tends to become more highly mechanised, particularly for the larger sizes of castings. There are, however, no standard machines made for this purpose. They are more in the nature of rather elaborate mechanised rigs or jigs and fixtures, designed by the die-casting companies to suit their own particular needs. Two ingenious examples are to be found at The Perry Barr Metal Company Ltd. in connection with the production of gear boxes and differential carriers. These are made by what the Americans call a "semi-permanent" moulding process, in which a sand core is used in conjunction with a die-cast exterior. In the case of the gear box (Fig. 1), the bell housing is completely die-cast (inside and out), while the gear-box portion is die-cast outside, with a sand core for the complicated interior. This component, which

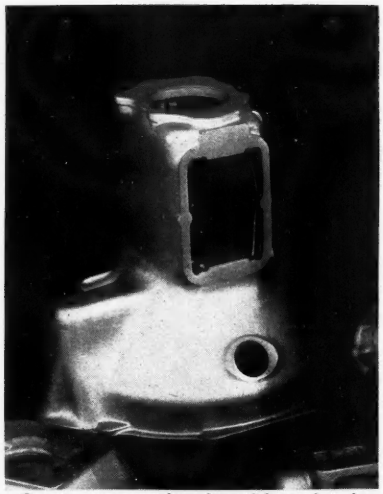

Fig. 1. Gravity-cast gear box, in which the interior of the box portion is a sand core.
(Courtesy of Perry Barr Metal Co., Ltd.)

weighs 14 lb and which is cast on end, is approximately 14 in. overall, the box cross-section being 7 in. × 7 in., and the bell housing an average of 14 to 15 in. diameter. In operation, the sand core of the box is placed on the internal die section of the bell housing, and the outer dies are closed by hand-operated rack-and-pinion motion and locked by straps under hydraulic pressure. The metal is poured, the setting period being gauged by an electronic timing device. When the metal is set, the straps are released, the die is opened, and the bell-housing interior die withdrawn hydraulically.

Fig. 2. A fully automatic casting machine for producing differential carriers.
The sand cores can be seen on the left of the machine table and also between the dies. The compressor and electronic devices are housed in the frame on the left.
(Courtesy of Perry Barr Metal Co., Ltd.)

The apparatus (Fig. 2) for manipulating the differential carrier dies is even more of a machine, since all the movements are automatic, with power cylinders, or jacks, to move the core into the dies, to close the dies, and to open them again after the casting is poured and set. The setting period is controlled by an electronic device which causes the cylinders to function automatically. The operator's duties are limited to ladling the metal and to removing the casting after the completion of the cycle, which he initiates by push-button

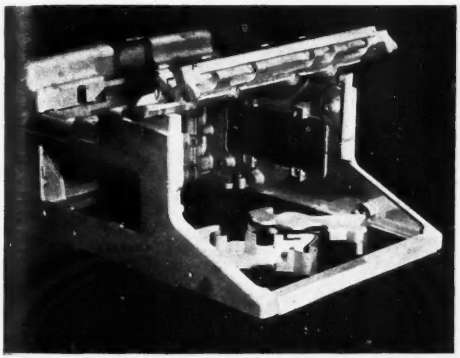

Fig. 3. **Typewriter-frame components, all of which are pressure die-cast, with the exception of the carriage, which is a gravity die casting.**
(Courtesy of Birmingham Aluminium Casting (1903) Co., Ltd.)

control. With some re-designing it would be possible to use all-metal dies for at least one of these components —the gear box—and so avoid the use of sand cores, but the method adopted is not only more economical but is also perfectly satisfactory.

Tolerances in Gravity Die Castings

Gravity die castings can be held to much closer tolerances than sand castings. The foundry can work to $\pm$ 0·010 in., and, where essential, to $\pm$ 0·005 in. Centre distances can be held at $\pm$ 0·005 in. The draft required on cores and on the side walls of small castings is a minimum of one degree included angle. The walls of larger components should be allowed a draft of one degree per side ; such an amount would be necessary, for instance, on an open box casting of 6 × 6 × 4 in. deep. Such figures, naturally, depend on the nature of the design and, when possible, greater allowances will be helpful. The thickness of the sections should not be less than 0·125 in., and machining allowances from 0·0312 to 0·0625 in., according to the size and nature of the component.

Pressure Die-Casting Machines

In the case of pressure die-casting machines, there is a fair range of British, American, and Continental plant from which to choose and which is designed by machine-tool manufacturers. These machines come in a wide variety of sizes with varying locking and injection pressures to suit. Originally, die-casting machines were of the " goose-neck " or " air-blown " type, in which the molten metal was forced into the die by air pressure of approximately 600 psi. This method, which is little used to-day, gave a very accurate reproduction of the die cavity, but it has disadvantages, among which is a tendency to porosity in the castings and a liability to considerable iron " pick-up " from the holding pot, with a consequent deleterious effect on the alloy.

The second system is known as the " hot-chamber " method. In this, the casting cylinder is immersed in the molten metal, whence a pneumatically operated plunger " pumps " the metal into the die. These machines are open to the same objection regarding iron " pick-up " and, while they are eminently satisfactory for zinc-base castings, they are not suitable for aluminium die casting. Many of the " hot-chamber " machines now on the market can be fitted with " cold-chamber " attachments, and *vice versa*.

The third method is one which is universally in use for making aluminium die castings for engineering and other purposes where close and strong metal is essential. This is known as the " cold-chamber " system. The " cold-chamber " machine consists of two main assemblies. The first is the die-holding and operating mechanism, which is usually mounted on four stout steel bars. There are, however, machines in which the bars are replaced by a cast structure. The bars carry a fixed platen, which holds one half of the die—this is the injection end of the machine. A moving platen also mounted on the bars holds the other half of the die. This moving platen is actuated by hydraulic pressure applied by means of a crosshead through toggle links. This mechanism closes the die, stressing the machine bars sufficiently to ensure that the dies are locked tightly enough to avoid excessive flash on the joint or injury to the operator, caused by escaping metal. The injection mechanism consists of a hydraulic cylinder, operating an injection plunger which slides in the injection cylinder. A port is cut in this cylinder, into which the molten metal is ladled. When the dies are locked, the injection plunger advances, seals the port, and forces the trapped metal into the die under a pressure which may be as high as 30,000 psi. The amount of metal ladled into the chamber is always more than that required to make the casting, and this surplus forms a slug which is ejected with the casting. After the casting cycle is completed, the cores, if any, are withdrawn and the casting is ejected by the die mechanism.

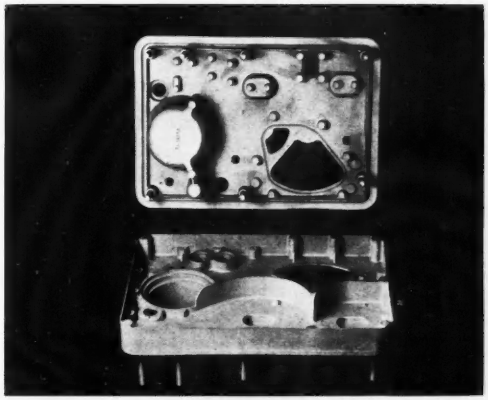

Fig. 4. **A pressure die casting of a panel for a combined receiving and transmitting radio set.**
The seven extended pillars are duralumin inserts, cast in position.
(Courtesy of Birmingham Aluminium Casting (1903) Co., Ltd.)

Some modern machines are fitted with electronic controls with a cycle in which (a) the dies are closed, (b) there is a dwell, (c) the metal is poured, (d) the injection plunger operates, (e) there is a further dwell for solidification, (f) the cores are withdrawn, (g) the dies are opened, and (h) the casting is ejected. Where the metal is hand-ladled, the first three operations are carried out by the operator. The advantage of this controlled operation lies in the fact that it allows sufficient time for the casting to solidify, but there is no lost time due to faulty sequence by the operator.

Some machines are fitted with an electric eye, to

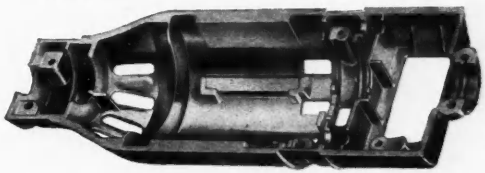

Fig. 5. **Half case of an electric hand tool, showing the type of complicated coring which can be achieved in pressure die castings. Each half case weighs 4·75 oz.**
(Courtesy of British Die Casting and Engineering Co., Ltd.)

prevent the machine from working if there is any danger to the operator. Most of the machines sold are of the self-contained type, with the hydraulic pump built into the machine, but some die casters prefer a centralized hydraulic service with pumps and an accumulator. This is more economical when a complete set of machines is to be laid down and future extensions can be reasonably well estimated.

Fig. 6. **Casing for a hearing aid, the two parts of which, made as pressure die castings, weigh a total of 2·5 oz.**
(Courtesy of British Die Casting and Engineering Co., Ltd.)

Designing for Die Casting

In designing for die casting it is essential to remember two main points, i.e., that under-cutting should be avoided wherever possible and that there should preferably be no violent changes from thin to thick sections. If the designer keeps in mind the fact that the die-casting machine is virtually a press with an open-and-shut motion, the component will be more likely to take a form which can be cast without difficulty. It is, of course, quite in order to have withdrawable cores, and in many instances these can be mechanically operated; nevertheless, it is as well to keep simplicity well to the fore.

Simple means of obtaining what at first glance appears to be a difficult result is exemplified by the design of toy motor cars and motor buses. The window openings were not made by withdrawable cores but by projections on the main die, which, by means of a "tumble-home" curve on the body, provided the openings, while still keeping a "true-to-life" appearance. In this case the thickness of the metal was only about 0·035 in.; therefore, the "tumble-home" had no need to be excessive in order to achieve the desired results. It is in respect of such apt solutions of difficult problems that the "job die-caster," as supplier to the finishing trades, gives a most valuable service.

Fig. 7. **A gravity-cast commercial vehicle gear box with associated components, comprising (left to right) flywheel housing weighing 20 lb, gear box (70 lb), clutch housing (14·5 lb), and clutch cover plate (4·75 lb).**
(Courtesy of The Northern Aluminium Co. Ltd. and Albion Motors Ltd.)

Component designs intended for production by other processes are not necessarily satisfactory for die casting; the component must therefore always be considered from the point of view of die casting, if the most satisfactory results at the most economical cost are to be attained.

The parting line of the dies should, for preference, be in one plane. This is not absolutely essential but, when this is the case, both the casting and the trimming dies are cheaper to produce and easier to maintain. Occasionally, it is essential that the die joint should follow a contour, but there should be a good reason for this departure from the simple rule.

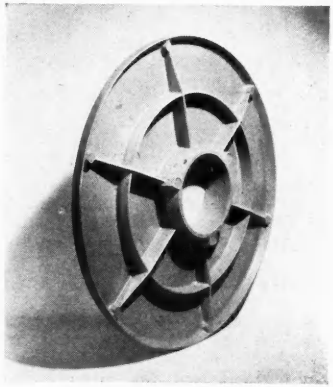

Fig. 8. **Pressure die-cast textile beam flange, 17 in. in diameter and weighing 5·5 lb.**
(Courtesy of High Duty Alloys Ltd.)

It is most desirable to avoid sudden changes from thick to thin sections and, where these changes are necessary, they should be gradual and fillets should be provided, wherever practicable. It is difficult to feed large masses through small channels and this must be taken into account in the product design. The heavier parts should preferably be near the runner and on occasions more than one runner may be required. Overflow wells provide a useful device for ensuring that the remote parts of a casting are properly fed. The minimum thickness of the walls of small castings can be in the neighbourhood of 0·035 in., while larger castings would require at least 0·08 in. The minimum diameter of cast holes is 0·125 in. Tapers in cored holes should be as generous as can be allowed, with minima of one degree on diameters up to 0·375 in. and 1·5 deg. up to, and 2·0 deg. over, one inch diameter. The draft on side walls should not be less than 0·010 in. per inch of depth but, unless the amount of draft interferes with the designer's purpose, it should be as much as is reasonably permissible. The greater the draft the easier it is to extract the castings from the die and, of course, the greater the speed of production.

Pressure die castings can be produced with greater dimensional accuracy than is obtainable by any other casting method; moreover, the castings are uniform and consistent in all respects, including the weight of one casting and another from the same die. Internal shapes which would be regarded as commercially impracticable by machining methods can be readily achieved in die castings. Pressure-tight castings can be produced, provided they are properly designed and developed for this purpose. X-rays are a very valuable aid in the development of such castings. The accuracy is such that assembly from the trimmed die casting is often possible without the necessity for machining; for instance, except where very great accuracy is required, register fits can be made without tooling of any sort.

Integrally cast rivets can be used to facilitate assembly. Furthermore, it is possible to include a wide variety of "incast" pieces, in addition to studs, nuts, and bushes—laminated inserts for magnetos are one example among many.

Uses of Aluminium Die Castings

Wherever economy in weight, coupled with strength and resistance to corrosion, is important, aluminium die castings will be found :—In aircraft, in automobiles, particularly public-service vehicles, in home appliances, in office machines, in machine tools, in radio and television, in instrumentation, in scientific and photographic apparatus, aluminium die castings, both gravity and pressure, play a full part, some idea of the diversity of which is shown in Figs. 3 to 10. Insofar as pressure die castings are concerned, home appliances are second only to automobiles, with a proportion of roughly 80% of the automobile figure. This is based on information provided by the American job-shop die casters and there is reason to believe that it is also true of the United Kingdom. It certainly would be, if plumbing, heating, and builders' hardware, much of which is domestic, is included in the total.

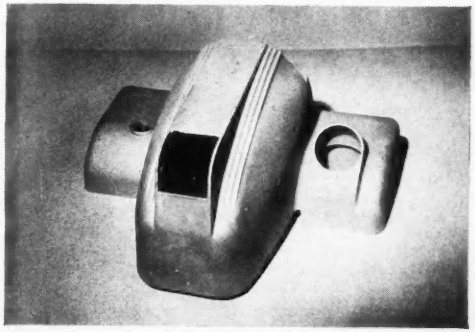

Fig. 9. **Front view of a pressure die casting of a vacuum cleaner, weighing 4·44 lb.**
(Courtesy of High Duty Alloys Ltd.)

Die castings are popular because they lend themselves to the best in modern product styling. If components are designed to suit the material, as indeed they always should be, they have an appearance of solidity and massiveness which can never be achieved by pressed parts. Reeded motifs and other patterns can be employed most effectively, while ribbing and beading can give a finish which is most attractive, added to which monograms and other insignia can be introduced. It goes without saying that streamlining is not only possible but desirable for a process which involves "hot hydraulics" as a fundamental. Finishes of many kinds are available :—Plating is possible, chemical and sprayed cellulose finishes, and colour anodising are frequently used, but possibly the clear or the silver anodising, which so beautifully maintains the natural colour of the metal, is the most effective.

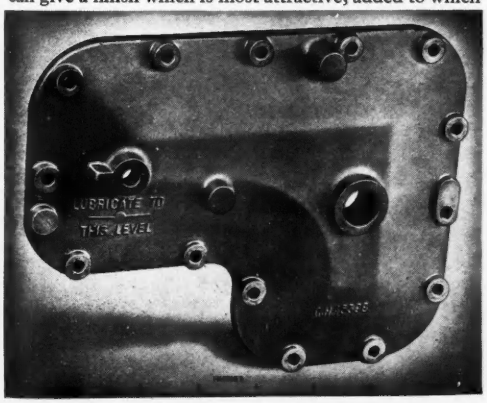

Fig. 10. **Pressure die casting of an oil cover, showing how clearly instructions can be cast.**
(Courtesy of Birmingham Aluminium Casting (1903) Co., Ltd.)

In one hundred years aluminium has made history as a structural material for engineers, and within the last half century the gravity and pressure die-casting processes have shown how this metal can be pressed into the service of the mass-production industries to the great advantage of all concerned. The future is rich with promise for these processes and this metal.

The Metallurgical Control of High-Quality Aluminium Forgings

(*Concluded from page* 238)

can often be used to minimize the possibilities of cracks occurring in the heat-treatment process and to reduce the incidence of distortion in the final machining operation.

Considerable work is also being carried out on the effects of various types of surface treatment and protective coatings, since it has been established that anodic treatment can, in certain circumstances, lead to accelerated failure of components. It has been explained above, however, that anodic treatment is used not only for surface protection but also as a process of inspection and it is therefore imperative that means should be found to modify the anodic process, to render it entirely suitable in all circumstances, or that another method of protection should be developed which would have all the advantages of anodising without its defects.

Other lines of development relative to the manufacture of components are aimed at the rejection or elimination of the slight weaknesses which are sometimes associated with the flash-lines of stampings and pressings. It is possible that in the future this may be overcome by the development of alloys with mechanical properties in the transverse direction equal to those in the longitudinal direction or by developments arising from the special studies now being undertaken of various methods of pre-forging stock material to minimize the flash-line effect in the finished article. Further work in this latter direction is being done by the development of the back-extrusion method of production, which is particularly applicable to cylinders and similar hydraulic components, while, with other types of complex articles, considerable progress is being made with the use of totally enclosed dies producing components substantially without a flash-line.

Conclusions

The experience acquired by the development and use of such techniques as have been outlined are naturally available to all users of forgings, since, as stated above, while general engineering products do not require such precision and perfection, the personnel who plan and produce the general article are also those who are in day-to-day contact with the needs of the aircraft industry, and their accumulated knowledge is automatically applied to the benefit of all users of forged products.

Acknowledgements :—

The author acknowledges his thanks to the Directors of Southern Forge Ltd. for permission to publish this article. He wishes, however, to make it clear that the views expressed therein are his own and not necessarily those of his Company.

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Finishes for Aluminium

By A. W. Brace, A.I.M.*

In common with most metals a wide range of finishes of both utilitarian and æsthetic value can be produced on aluminium. Aluminium can be given conventional treatments, such as painting, lacquering, or stove enamelling, whilst even vitreous enamelling has become possible. Special mechanical treatments, such as rolled-on patterns, shot blasting, or wire brushing, can be easily applied, although, as is the case with chemical finishes such as etching, these surfaces are often rendered more durable and attractive by anodising. This anodic film can be dyed to give a wide range of colours. Plating of aluminium with other metals such as copper, silver, nickel, and chromium is also practised commercially.

It must be appreciated that the term "aluminium" is a generic one, covering a range of materials having a rather different response to the various surface treatments used, owing to the effect of alloying elements. This factor will be discussed in more detail under the sections dealing with the various processes mentioned above.

Applied Finishes

Mechanical Finishes :—

Almost any of the various grades of aluminium and its alloys can be provided with mechanical finishes. Aluminium sheet rollers have a standard range of patterns which are adequate for most purposes. Apart from embossed diagonals and circular spot patterns, embossed impressions providing imitation stucco finishes or various forms of fluting are available. A selection of these is shown in Fig. 1. A matt surface produced by wire brushing can also be obtained on the sheet, a range of textures being produced by changing the diameter of the wire in the brushes used. The use of such material demands that it must not be handled unduly roughly during fabrication.

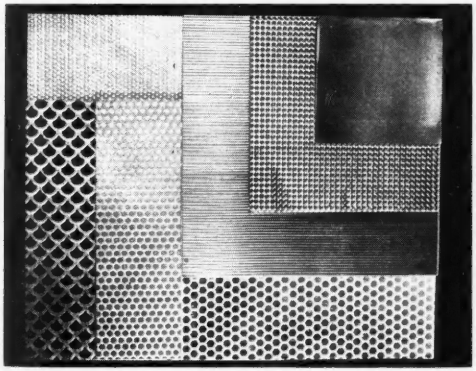

Fig. 1. **Types of patterned aluminium sheet produced by rolling mills.**

If it is not possible to utilize any of the mill finishes mentioned, similar treatments can be carried out on the finished product, although the cost is usually appreciably higher. Hammering and engine turning are examples of mechanical finishes applied to finished products where a high-quality product is required. Patterns can be rolled on the surface with suitable tools. One way of obtaining a matt finish is to shot-blast lightly with non-metallic abrasives; etching can also be used but, unlike shot blasting, it is not easy to apply to local areas. Both surfaces are readily fingermarked unless protected by clear lacquer or anodising.

Owing to the high corrosion resistance of aluminium, it is often quite satisfactory to leave the article without any protective finish but, to enhance its sales appeal, it may be polished. The principal requirement is that the abrasive used should not leave any harmful residues; carborundum or alundum abrasives are favoured. For polishing, Vienna lime and Tripoli paste are employed some care being needed to avoid too heavy a pressure in polishing; otherwise, characteristic streaks, sometimes referred to as "comet's tails," may be produced. Barrel polishing can often be used as an economical method for finishing castings, stampings, or even small lengths from extrusions.

Chemical Finishes :—

Chemical finishes are occasionally employed on aluminium, although they are but rarely used alone. A light matt etch may be used, such as on hollow-ware, but usually the matt surface is protected by anodising. The chemical treatments commonly used on aluminium provide a surface film which will be a good paint base, since poor adhesion is otherwise encountered with many types of organic coating.

The oldest of these processes is known as the M.B.V. (Modified Bauer-Vogel) treatment, which uses a mixture of sodium carbonate and sodium chromate, and yields a light grey film that can be dyed to give a limited range of colours. However, these films are very thin and the light-fastness of the coating will be limited. Usually, they are used for colour-identification purposes where long life and reproducibility of colour shade are not of major importance.

As mentioned previously, these processes are primarily used as a paint base and a number of satisfactory proprietary processes have been developed since the original M.B.V. bath was announced. Several of these are alkali chromate mixtures essentially similar to M.B.V., but represent some improvement over the original. More recently, acidic mixtures, usually containing phosphoric, chromic, and hydrofluoric acids or their salts, have been developed and these give very good coatings in appreciably shorter times than the alkali chromate solutions. Table I indicates the main proprietary chemical processes now available in Great Britain :—

Table I. Chemical Processes for the Pretreatment of Aluminium for Painting.

Alkali Chromate Type	Acidic Type
M.B.V.	Chrome-sulphuric (DTD 915A) pickle
Pylumin (Pyrene Co. Ltd.)	Alocrom 100 and 1200 (Imperial Chemical Industries Ltd.)
Walterisation "L" (Walterisation Co. Ltd.)	Bonderite 170 and 710 (Pyrene Co. Ltd.)
Alrok (Alumilite and Alzak Ltd.)	Jenolite AKS (Jenolite Ltd.)
	Aloclene (Sunbeam Anti-Corrosives Ltd.)

Where chemical pretreatment by dipping is not possible, satisfactory adhesion can be obtained by using solutions which the same companies offer and which can be brushed or swabbed over the surface of the metal.

Paint Finishes :—

Painting practice for aluminium follows conventional lines and there are only a few points to be noted in which practice differs from that adopted for other metals. For the protection of structural steel, red-lead primers are frequently used, but these should preferably be avoided with aluminium, especially where protection against marine conditions is required. Primers containing a proportion of zinc chromate are preferred for protecting

* Metallurgist, The Aluminium Development Association, London.

TABLE II. GUIDE TO THE SELECTION OF ANODISED AND PLATED FINISHES FOR WROUGHT ALLOYS.

Material Designation (BS. 1470-1477) (Draft Revision 1955)	Nominal Composition	Protective Anodising	Anodising and Dyeing	Bright Anodising	Plating
1	99·99% Al	E	E	E	N.R.
1A	99·8% Al	E	E	E	N.R.
1B	99·5% Al	E	V.G.	V.G.	V.G.
1C	99·0% Al	V.G.	G	G	E
N3	1¼% Mn	V.G.	G	M	G
N4	2½% Mg	V.G.	V.G.	G	†
N5	3½% Mg	V.G.	V.G.	G	†
N6	5% Mg	G	G	M	†
N7	7% Mg	M	M	M	U
H9	½% Mg, ½% Si	E	V.G.	G	†
H10	1% Si, ¼% Mg	V.G.	G	M	†
H11	1¼% Cu, 1% Si, 1% Mg	G	G	M	G
H12	2% Cu, 1% Ni, 1% Mg, ¾% Si	M	M*	U	V.G.
H14	4½% Cu, ⅝% Mn, ⅝% Mg	M	M*	U	V.G.
H15	4½% Cu, ½% Si, ⅜% Mn, ½% Mg	M	M*	U	V.G.
H17	4% Cu, 2% Ni, 1½% Mg	M	M*	U	V.G.
H18	2½% Cu, 1½% Mg, 1½% Ni	M	M*	U	V.G.
H20	1½% Cu, 1% Mg, ⅝% Si	V.G.	G	M	†
H30	⅝% Mg, 1% Si, ⅝% Mn	V.G.	G	M	†

E, excellent ; V.G., very good ; G, good ; M, moderate ; U, unsuitable ; N.R., not recommended.
* Suitable only for dark colours.
† A modified etching technique prior to plating is essential and some initial difficulties may occur.

aluminium. Finishing coats can be of any good type, provided they are compatible with the zinc chromate primer.

Coatings based on vinyl resins are often favoured for aluminium, since they will give good adhesion without chemical pretreatment of the metal. The new epoxy resins are also attractive in this respect, but good adhesion without pretreatment at present appears to be obtained only when stoved finishes are used.

ANODISING

Anodising consists essentially of making the fabricated article the anode in a dilute acid electrolyte (usually sulphuric acid) and passing a current so as to produce an artificial oxide layer on the surface of the aluminium. This coating is porous, can absorb dyestuffs, and can subsequently be sealed, but it is also harder than the basis metal, although this characteristic can be varied by adjusting conditions to produce films ranging from soft and flexible to coatings of extreme hardness and wear resistance.

Choice of Materials :—

It is not sufficiently realized by designers and buyers that the grade of aluminium or the composition and manufactured form of an aluminium alloy has an important influence on the response of any component.

Whilst all aluminium alloys can be anodised, they do not all respond to the same degree, and in fact some alloys are difficult to anodise and require conditions which are not readily achieved in the average anodising plant. As a general guide, it can be said that aluminium of 99·0 to 99·99% purity (materials 1, 1A, 1B, 1C)* and the principal aluminium-magnesium alloys (N4, N5 & N6) anodise readily and give the most satisfactory results. Heat-treated alloys of the aluminium-magnesium-silicon type (H9, H10, H20, H30) are also quite satisfactory, but those containing appreciable quantities of copper require special treatment. With the casting alloys similar considerations apply, but the choice of suitable materials is made more difficult by the fact that the alloys preferred by founders often have a high silicon content and in consequence are difficult to anodise, especially if a hard wear-resistant film is required.

In order to provide some guidance to the designer, Tables II and III have been prepared, summarising the suitability of the British Standard General Engineering Alloys for various anodised finishes and for electroplating. The comments made in the preceding paragraph apply principally to protective anodising, but certain grades of aluminium respond to a brightening treatment, so that with aluminium of the highest purity the

*Note :— These designations are those used in BS. 1470-1477 (wrought materials) and BS. 1490 (cast).

TABLE III. GUIDE TO THE SELECTION OF FINISHES FOR CAST ALLOYS.

Material Designation (BS. 1490) (Draft Revision 1955)	Related DTD or L. Spec.	Nominal Composition	Protective Anodising	Anodising and Dyeing	Bright Anodising	Plating
LM1M	DTD 428	7% Cu, 3% Si, 3% Zn	M	U	U	V.G.
LM2M		10% Si, 1½% Cu	M	U	U	M††
LM3M		12% Zn, 3% Cu	M	U	U	M
LM4M & 21M	DTD 424a	5% Si, 3% Cu	G	M*	U	G
LM5M	DTD 165a	4% Mg	V.G.	G	G	M**
LM6M	3L33	12% Si	M	U	U	M††
LM7M & 23P	L51	2% Cu, 2½% Si, 1¼% Ni	V.G.	G	U	V.G.
LM8M, LM8P, LM8W, LM8WP	DTD 716, 722, 727, 735	4½% Si, ½% Mg	G	M*	U	M††
LM9W or WP	DTD 245a	12% Si, ½% Mg	M	U	U	M††
LM10W	L53	10% Mg	M†	M†	M	M**
LM11W or WP	DTD 298a, 304a	4½% Cu	G	G	M	V.G.
LM12WP		10% Cu, ¼% Mg	M	M*	U	G
LM13WP		12% Si, 2½% Ni, 1% Mg	U	U	U	M††
LM14WP	2L35	4% Cu, 1½% Mg, 2% Ni	M	M*	U	V.G.
LM15WP	L52	2% Cu, 1¼% Ni, 1% Mg	G	G	U	V.G.
LM16W or WP	DTD 272, 276	5% Si, 1¼% Cu, ½% Mg	G	M*	U	M††
LM17M		12% Si, 3% Ni	M	U	U	M††
LM18M		5% Si	G	M*	U	M††
LM20M		12% Si	M	U	U	M††
LM22W		5% Si, 3% Cu	M	M*	U	G
LM24M		4½% Si, 3½% Cu	M	U	U	M††

V.G., very good ; G, good ; M, moderate ; U, unsuitable.
* Suitable only for dark colours.
† Anodising conditions must be carefully controlled for good results.
** Can be plated satisfactorily, but is not recommended.
†† These alloys containing silicon require a modified treatment to get good adhesion.

reflectivity after brightening and anodising is superior to that of chromium plate.

The materials referred to in these tables are not all covered by the existing British Standards, but those which have been included are expected to appear in the revised standards—B.S. 1470-1477 (wrought materials) and B.S. 1490 (cast)—when these are published.

The response of a material to bright anodising depends upon its purity and its surface condition. By careful control of production conditions, material can be produced having an excellent response to bright anodising. Material rolled under normal conditions, when anodised, gives a slight streakiness on the surface, this being due to microscopic surface imperfections associated with the rolling direction.

Whilst this streakiness does not represent any defect in the material, it mars the appearance and it is necessary, when ordering material where a high-quality reflective surface is required, to specify "anodising quality" material which has been prepared in a manner which will meet these exacting requirements.

The brightness obtained depends upon the purity and, whilst quite satisfactory brightness can be obtained on aluminium of 99·2% purity by chemical brightening, it is usual to employ material S1B (99·5% Al min.) for reflectors, although, for more exacting conditions where maximum reflectivity is required, super-purity aluminium S1 (99·99% Al) is used. These are the two most commonly used grades, although there is still some use of S1A (99·8% Al), which gives intermediate results.

Good response to bright anodising can be obtained from aluminium-magnesium alloys NS4 and NS5, since these are often produced from aluminium of at least 99·5% purity, but are appreciably stronger. More recently, super-purity aluminium-magnesium alloys have been developed and these give the high reflectivity of the 99·99% material, but are stronger and harder, thus widening their field of application. Some manufacturers can offer material clad with a thin layer of super-purity aluminium but this requires careful manipulation. Bright-anodised super-purity aluminium-magnesium alloy strip has already been used for motor-car trim on the Continent, particularly on the Volkswagen, and its adoption in Great Britain can be anticipated in the near future.

Specifying Anodic Finishes :—

British Standard 1615 "Anodic Oxidation Finishes for Aluminium and Aluminium Alloys" was first published in 1949 but it is not as widely used by purchasers as it should be. In common with many other standards, it does not attempt to specify how anodising shall be carried out but seeks instead to lay down certain minimum film thicknesses according to the application and to specify other properties which will guarantee a minimum standard of quality. The standard is now under revision and will be issued in the near future. It is not enough to stipulate that "the anodising shall be to B.S. 1615," since this leaves the matter solely in the hands of the anodiser, who cannot be assumed to know the conditions of service.

TABLE IV. MINIMUM THICKNESS OF ANODIC COATINGS. (B.S. 1615 : *Draft Revision*)

Application	Chromic acid electrolytes*, microns	Sulphuric acid or oxalic acid electrolytes*, microns
Interior decorative work	2·5	5·1
Coatings exposed to weather	3·8†	15·4†
Coatings for subsequent painting	1·3	5·1
Lighting reflectors for internal use	—	5·1
Lighting reflectors for external use	—	15·4†
Heat emitters	—	5·1
Special purposes	As agreed between manufacturer and purchaser.	

* The films produced by these processes are not strictly comparable, each having its own special applications.
† This thickness may not be obtainable on some classes of aluminium alloys.

The Standard has a series of clauses, one of which refers to thickness of coating and includes a table of minimum thicknesses, reproduced as Table IV.

If the component is to be used out-of-doors, or even in semi-exposed conditions, such as the interior of a ship, it is essential to have the minimum thickness of 15·4 μ (0·0006 in.) given in the Table. The material should also be required to pass the Sealing Test, which ensures that the anodic film has been properly sealed after anodising.

Reflection Values :—

Where the application is such that reflectivity is of importance, reference should again be made to the appropriate Clause and Table in the Standard. For applications where reflection of light is involved, three grades of reflectivity are available, and the total, specular, and diffuse reflectivity values which correspond to these grades are given in Table V.

TABLE V. WHITE LIGHT REFLECTION FACTORS. (B.S. 1615 : *Draft Revision*)

Grade of Reflector	Application	Total reflection factor, %	Specular reflection factor expressed as a percentage of total reflection factor, %
A	Internal External	82	99
B	Internal	77	96
	External	69	96
C	Internal	67	85
	External	60	75

In addition to being a good reflector of light, bright anodised aluminium is an excellent reflector of infrared and the B.S. requirements for heat emitters are given in Table VI.

TABLE VI. INFRARED REFLECTION FACTORS. (B.S. 1615 : *Draft Revision*)

Grade of reflector	Total infrared reflection factor, %
N	85
O	80
P	70

Dyed Anodised Finishes :—

Since the anodic film is porous when the article is removed from the anodising bath, it can be dyed prior to sealing. It is customary to use organic dyestuffs, the permanence of which depends upon the thickness of the anodic coating and the light-fastness of the dyestuff. This is referred to in B.S. 1615, which requires that the light-fastness performance number must be not less than 3 for internal work or not less than 7 for external work. Some consideration must be given to the interpretation of the terms "internal" and "external" since, for example, railway-carriage fittings should be treated as an external application, since they can be exposed to quite strong light. It is interesting to note that recently several multi-storey buildings in the U.S.A. have been clad with colour-anodised aluminium panels. An anodic film thickness of 0·0008 to 0·0010 in. is used and several of the colours recommended are based on inorganic pigments, although a limited number of organic dyestuffs are also suitable. This development promises to become of importance in Great Britain in view of current interest in curtain walling.

ANODIC COATINGS FOR WEAR RESISTANCE

The anodic layer produced on aluminium can be used to provide components with a wear-resistant surface comparable with that of cyanide case-hardened steel. It must be appreciated that the hardness of the coating depends upon anodising conditions, particularly the forming voltage and electrolyte temperature. There is no sharp distinction between hard and soft coatings

but only a gradual change of properties as the temperature of the electrolyte is lowered and the applied voltage raised.

This means that either the designer must depend upon the knowledge and experience of the anodiser or that some test must be devised which will measure the hardness and wear resistance of the film. Ordinary indentation hardness measurements are of limited value, since the coating is slightly porous and the hardness reading is also affected by the properties of the basis metal. However, micro-hardness readings on coatings of around 0·002 in. in thickness indicate that values of around 450 to 550 VPN can be obtained on hard anodic coatings, as compared with 200 to 250 VPN on thick coatings produced under conditions which would be expected to give soft coatings.

Nevertheless, there are only limited hardness data available and the values recorded are not entirely consistent. A further limitation is that hardness determinations are not possible for coatings of less than 0·001 in. thickness, though film thickness of 0·0005 to 0·0015 in. are quite adequate for some purposes. The most satisfactory test for assessing the abrasion resistance of an anodic coating is the Schuh and Kern Test. In this test a stream of fine carborundum particles (150-mesh grit) under an air pressure of 5 psi is directed at the anodised surface, which is held at 45 deg. at a fixed distance from the nozzle.

The hardness of an anodic coating depends upon the operating conditions during anodising and this can best be illustrated by reference to Table VII, which gives the Schuh and Kern values for anodic coatings produced under various conditions, using 150-mesh carborundum powder and 5 psi air pressure.

TABLE VII. ABRASION RESISTANCE VALUES FOR ANODIC COATINGS ON NS5 ALLOY PRODUCED UNDER VARIOUS CONDITIONS.

Electrolyte	Coating thickness, microns	Carborundum to penetrate, grams	Specific abrasion resistance, gm/micron
20% (by vol.) H_2SO_4	11	374	33
7% (by vol.) H_2SO_4	10	771	77
Hard anodising	46	5232	114

It is possible to achieve a specific abrasion resistance as high as 200 gm/micron, but these coatings are extremely brittle and tend to flake under slight impact or stress. For normal conditions, coatings with a minimum specific abrasion resistance of 50 gm/micron will give satisfactory service, and a coating thickness of 5 to 15 μ is adequate. However, for the very arduous conditions encountered in the moving parts of mechanisms, it may be desirable to use thick hard coatings, and a minimum film thickness of 38 μ is recommended, with a specific abrasion resistance of 100 gm/micron, although this abrasion value may be specified for thinner coatings, such as are required for protecting bright finishes against severe abrasion, without any significant loss of reflectivity.

Applications of Hard-Anodised Coatings :—

There is naturally considerable interest in hard anodised coatings for aircraft hydraulic systems, since wear problems are often encountered on the reciprocating parts under heavy loads. Probably the largest jobs so far processed in this way are the undercarriage legs for the Bristol "Britannia" and the Avro "Vulcan". Fig. 2 shows a leg from the Vulcan bomber which is almost 5 ft in length, the central sleeve (A), which is hard-anodised, being 9 in. in diameter. It is usual to lap the surface lightly after hard anodising and, where close dimensions are required, due allowance should be made. There is a growth in dimensions upon anodising, usually around one-third to one-half the coating thickness, depending upon the alloy, method of manufacture, and anodising conditions. The precise allowance should be established on the prototypes.

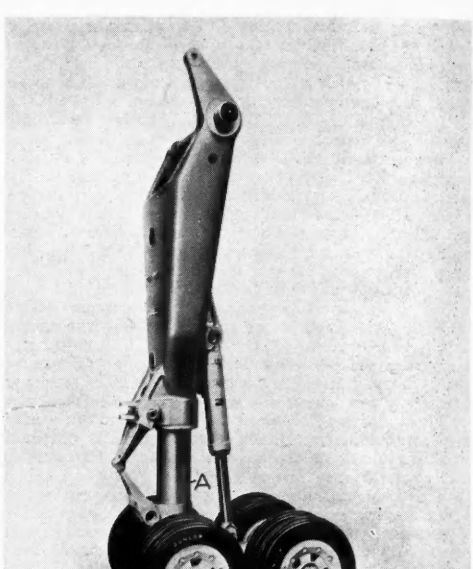

Fig. 2. **Dowty undercarriage for "Vulcan" bomber.** (Courtesy of Dowty Equipment Co., Ltd.)

Small gears have been hard-anodised and oil-sealed, in order to provide self-lubrication under light loading conditions. Where conditions are more arduous, the working temperature may be moderately high, in which case the gears should be flooded with lubricant. Exposure to temperatures higher than 150 to 200° C causes crazing of the coating and, if the loading is high, the coating may disintegrate. Small gears with 0·001 to 0·002 in. coatings have been successfully used in small machines for coin counting and ticket issuing.

Other applications include parts for wrapingp machinery, rollers used in box making, orthopædic appliances, hydraulic railway buffers, metal-spraying pistols, the cordite starter casing for a jet-engine starter, and the sliding faces of the head of an oxy-acetylene cutting machine.

Another important property of hard anodic coatings is their electrical insulation resistance. An electrical breakdown voltage of upwards of 1000 V can be obtained with coatings of 0·002 in. thickness, and in consequence several electronic equipment manufacturers have used hard anodised coatings in instruments, particularly where a conducting core and insulating surface are required. The advantage here is that the hard anodising can be applied to local areas of irregular shape by stopping off the rest of the surface.

PLATED FINISHES

Much attention has been paid in post-war years to the electroplating of aluminium, and the zincate process tends to be especially favoured in the U.S.A. In Great Britain some platers prefer an older process, often called the Vogt Process, in which, after cleaning and etching, a thin zinc flash is produced electrolytically, instead of by chemical replacement as with the zincate method. Its main advantage is that it will satisfactorily plate components containing steel inserts. On the other hand, it is not readily adapted to automatic plating.

(*Concluded on page* 252)

Aluminium-Alloy Bearings

By E. A. G. Liddiard, M.A., F.I.M.*

There is probably no other engineering application in which there is a greater diversity of materials at present in use than in bearings. Bearing materials vary from very soft metals, such as tin and lead, to the hardest known materials, for example, diamond and other jewels which are used in precision mechanisms. Base metals, such as lead, find themselves in competition with silver. Compromise becomes inevitable and a bearing material is chosen to suit a particular engineering application, so that the ideal bearing can only be defined in terms of its intended use. The use of aluminium and its alloys as bearing materials is comparatively recent and not too well known amongst engineers, but the fact that aluminium-alloy main bearings are or have been used in such different motor-cars as the Bentley and the Volkswagen and as the journal bearings of the Caterpillar tractor is evidence of the importance of these materials to the engineer. In this article the development of aluminium bearings will be traced and reasons given as to why aluminium-alloy bearings are likely to have wider applications in the future.

Fundamental Requirements of a Bearing Material

The properties required in a bearing are often mutually contradictory, and this accounts for the diversity of materials used as bearings. For example, some bearings need a high load-carrying capacity and resistance to fatigue but should preferably be soft enough to conform to the shaft and to allow hard particles to become embedded in the relatively soft bearing metal. It is sometimes an advantage for a bearing alloy to melt at a relatively low temperature, so that seizure, when it does take place, does not cause damage to the shaft; yet it is obviously important that the bearing should not run out unnecessarily.

The properties necessary in a bearing material were first closely studied by Bowden[1] and his collaborators at Cambridge, who made it clear that the prime cause of high friction between a bearing metal and the shaft is direct metal-to-metal contact, with the consequent welding of the high spots and tearing out of welded particles. To prevent this effect is the principal function of lubricants, which, by forming adherent monomolecular layers on the metal surfaces, prevent metal-to-metal contact. Friction is thus limited to the force necessary to shear the lubricant. None the less, in most applications it is necessary for a bearing metal to operate, at least for a time, under conditions in which the film of lubricant breaks down. Bowden has also shown that, when two substances are rubbed together sufficiently to cause polishing, the temperature reached at the interface corresponds to the melting point of the lower-melting-point substance, and in effect a very thin film of the lower-melting-point material is formed on the surface. Molten metal has negligible shear strength, and low-melting-point metals can in fact act as lubricants, provided, of course, that there is no question of interdiffusion between the two metals or the formation of hard intermetallic compounds with higher melting points. It is probably this ability to lubricate by virtue of their low melting point which accounts for the long and successful use of babbitt-bearing metals, and it is only under conditions of heavy loading and stress reversals that babbitts fail by excessive deformation or, more commonly, by fatigue, particularly at slightly elevated temperatures.

Metal-to-metal contact can also be prevented, at least under light loads, by the presence of metal oxides, but such oxides are not generally successful in preventing metal-to-metal contact, because there is a tendency for the oxide film to be broken down by the deformation of the metal underneath.

In an investigation on the pressure welding of metals, Tylecote[2] has shown that welding is accomplished more easily when a hard oxide film forms on a softer metal, since, once the oxide film has broken down, the oxides themselves may act as an abrasive and so increase the tendency to wear and the ability of metal surfaces to weld together. If, however, the basis metal is hard enough and the oxide film is thick and strong enough to withstand the applied load, it is possible for the oxide surface to become smooth and to operate at quite low coefficients of friction, similarly to hard steel pivoting on a gem. However, for this mechanism to operate, extremely close fits are necessary and loads must be relatively light.

It is an advantage if a bearing metal can have a high conductivity, so that frictional heat can be removed quickly. The bearing should also have approximately the same coefficient of thermal expansion as the material of the shaft, and should be sufficiently resistant to corrosion to avoid attack by lubricants or by the atmosphere when the bearing is being fitted or the lubricant has been washed away. The bearing should have adequate load-carrying capacity, and this usually means that it must not be too soft. The ideal to be aimed at is for a bearing to have load-carrying capacity sufficient for the intended use, together with sufficient softness and ductility to conform to the surface of the shaft and to allow hard particles to become embedded in the surface of the bearing metal without scoring the shaft. On the other hand, the bearing must have adequate resistance to wear and should be capable of carrying and maintaining a film of lubricating oil at the surface. It is for the latter reason that a bearing often consists of both hard and soft constituents, so that channels formed as a result of wear of the softer phase are available to permit the lubricating oil to reach all parts of the bearing surface. It is often necessary for the bearing metal to bond easily to steel, which provides a high-strength backing, but the ability of the bearing metal to bond to steel must not be linked with a tendency to stick to the shaft.

Development of Aluminium-Alloy Bearings

At first sight, aluminium would not appear to be a particularly promising base for a bearing alloy. The lightness of aluminium is not likely to be very important in bearings, though it is an advantage, and the high conductivity of aluminium is favourable. On the other hand, the thermal expansion of aluminium is high relative to that of steel, and aluminium oxide forms easily on its surface in the atmosphere and can be abrasive. In developing aluminium alloys for bearings, therefore, it is either necessary to raise the hardness of a basis metal, to avoid rupture of the aluminium oxide under load, or to provide some low-melting-point constituent which can squeeze out and form a fairly continuous film over the surface, thus preventing oxide formation as well as providing a metal lubricant.

Various alloying additions will harden and strengthen aluminium. Some stiffen up the metal by going into solid solution; others form harder intermetallic compounds which appear as harder constituents in a soft matrix, but the most effective hardening is obtained from additions whose solubility in solid aluminium decreases with temperature, thus allowing hardening by solution, followed by precipitation heat treatment. The most suitable addition to give metal lubrication by means of a soft low-melting-point constituent is tin, although lead, cadmium, and indium are also possible.

The initial stimulus to the use of aluminium as a bearing material came during the 1914-18 war, when an

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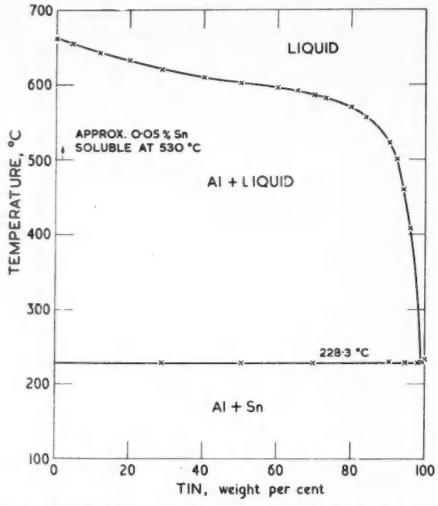

Fig. 1. **Equilibrium diagram for aluminium-tin alloys.**

acute shortage of tin developed in Germany; similar reasons led to the continued development of aluminium bearings during the last war. It is not surprising, therefore, to find that German aluminium-alloy bearings contain little, if any, tin. Cadmium, antimony, and lead are present in some of the German bearing alloys, but the emphasis has been more on strengthening and in providing alloys with duplex structures containing harder constituents. One of their most interesting developments is a high-silicon (20 to 25%) alloy, in which primary silicon is the harder phase in the duplex microstructure.

In England the first aluminium-base bearings to find any considerable application were the Rolls-Royce AC9 and AC7.[3] These alloys were developed before the war and were used in the as-cast condition. Tin is the principal constituent of both these alloys, 5½ to 7% in the case of AC9, and 4½ to 5% in the case of AC7. Both alloys contain small quantities of nickel. Other minor addition elements are copper, manganese, antimony, silicon, and magnesium.

Very similar alloys have been developed in America[4], where they are known as the Alcoa 750 alloys. These contain essentially 6½% of tin and about 1% of both copper and nickel, but one alloy (XA750) also contains about 2½% silicon. These alloys are also mainly used in the as-cast condition, although considerable efforts are being made to produce aluminium-base alloys backed to steel, and some of these processes may involve rolling of composite strip.

The reasons for the tin additions are obvious, but the function of some of the other alloying elements is not so clear. The silicon is presumably added to improve casting characteristics, and the other minor additions probably permit sufficient age hardening, in addition to strengthening the matrix, to give adequate load-carrying capacity.

Development of the Aluminium—30% Tin Alloys

It will be clear from the fundamental requirements of a bearing material that the addition of a material with a comparatively low melting point, which will form a separate phase and allow a metal lubricant to form on the surface, would be an advantage in aluminium-base bearings. Lead would be a possible addition, but unfortunately lead and aluminium are almost immiscible in the liquid state and they have widely different specific gravities. It is therefore difficult to introduce more than about 2% of lead into an aluminium-lead alloy, which gives only about ½% by volume. Cadmium suffers from a similar defect, but to a lesser extent. There is no difficulty in adding up to 5% cadmium to aluminium. However, the melting point of cadmium is higher than that of tin (321° C, compared with 232° C) and in normal times tin is available at a price rather less than half that of cadmium. The aluminium-tin equilibrium diagram (Fig. 1)[5] shows that there is no liquid immiscibility, and it is therefore possible to chill-cast aluminium-tin alloys with a wide range of composition. However, when the tin content exceeds about 7%, the interfacial tension between aluminium and the molten aluminium-tin eutectic is such that a continuous film of

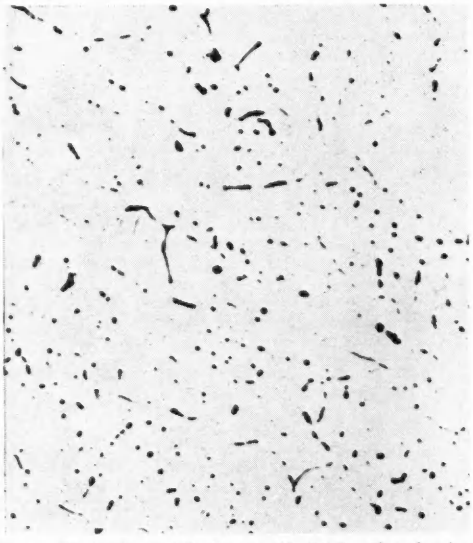

Fig. 2. **Photomicrograph of a cast Al—5% Sn alloy, showing discontinuous films and globules of tin. (× 150)**

Fig. 3. **Photomicrograph of a cast Al—15% Sn alloy, showing continuous films of tin. (× 150)**

substantially pure tin is formed round each aluminium crystal. Fig. 2 is a photomicrograph of an aluminium—5% tin alloy, showing discontinuous films and globules, while Fig. 3 is a similar photomicrograph of an aluminium—15% tin alloy; in these illustrations, tin appears black and aluminium white. It is possible to control the tin distribution to some extent by alloying additions, and useful work in controlling the distribution of tin in cast alloys has been done both in Britain and U.S.A. Copper and certain grain-refining elements will improve tin distribution, but the practical limit to avoid continuous films in a cast aluminium-tin alloy remains somewhere below 10%.

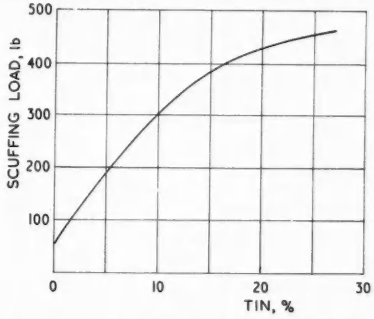

Fig. 4. **Improvement in the seizure resistance of aluminium by addition of tin (Hunsicker).**

There can be no doubt, however, that from the point of view of bearing characteristics the more tin there is in the material the better. Fig. 4 shows the results of some tests carried out by Hunsicker & Kempf on the resistance to seizure of aluminium-tin alloys. The scuffing load increases rapidly up to about 400 lb with about 17% tin, and when the tin content exceeds about 25% the seizure-load/tin-content curve begins to flatten.

Unfortunately, alloys with intergranular films of tin have low strength and low ductility at temperatures of 100 to 200° C. Figs. 5 and 6 show the variation in strength and elongation respectively of various aluminium-tin alloys in the as-cast condition at temperatures up to 300° C. Since the tin is in the form of a continuous film, the strength and fatigue properties are no better than for tin itself, and the films are particularly weak at the temperatures at which the average bearing has to operate. Fig. 7 shows the commencement of a fatigue fracture in a cast aluminium-tin alloy Wöhler-type specimen. It will be obvious that fracture has started along the weak film of tin at a grain boundary.

It was left to the investigators of the Fulmer Research Institute, working in collaboration with the Tin Research Institute[6], to develop a method of altering the distribution of tin in aluminium-tin alloys from a continuous intergranular film to discontinuous pools. It was found that, if the aluminium-tin alloy was cold-worked and subsequently heated to a temperature which would cause recrystallization of the cold-worked aluminium, the tin films were broken up, giving a structure which experience has shown to be exceptionally suitable as a bearing material. Fig. 8 shows the microstructure of an aluminium—30% tin—3% copper alloy in the as-cast condition, in which all the tin is present as a continuous film around the aluminium crystals.

As a comparison Fig. 9 shows the same alloy stretched by 20% at room temperature, followed by annealing for one hour at 500° C. The tin films have all become discontinuous. Fig. 10 shows the variation in elongation with temperature of alloys with an Al/Cu ratio of 98·2, containing up to 60% tin, which have been cold-worked by forging and which have subsequently been annealed for 1 hr at 350° C. The lower curve gives comparative data for a 10% tin alloy in the as-cast condition. As much as 60% can be added to aluminium, and when this is cold-worked and annealed, it has considerably higher ductility than the chill-cast aluminium—10% tin alloy at 100° and 200° C. There is no lowering of ductility in an alloy containing as much as 50% tin. This discovery opened up a wide field for new bearing alloys, since, by altering the alloy content of the aluminium matrix, it is possible to provide a range of bearing materials with a hardness range from about 20 Brinell up to approximately 100. By using a super-pure aluminium, the hardness could be kept at around 20 VPN, thus giving a high-conductivity alloy with a fatigue strength comparable with that of tin-base babbitt at room temperature, and about 50% higher at 100° C. Additions of hardening elements, e.g., copper, to the aluminium matrix, followed by suitable heat treatment,

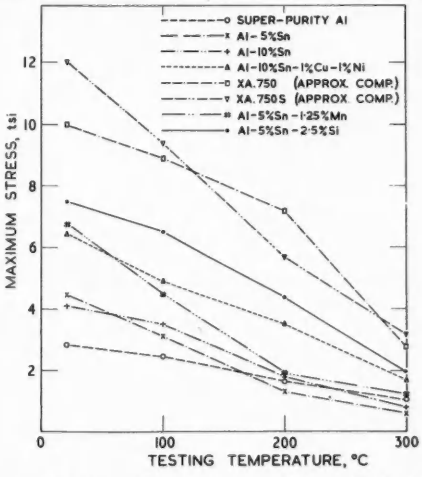

Fig. 5. **Variation with temperature of strength of various aluminium-tin alloys in the as-cast condition.**

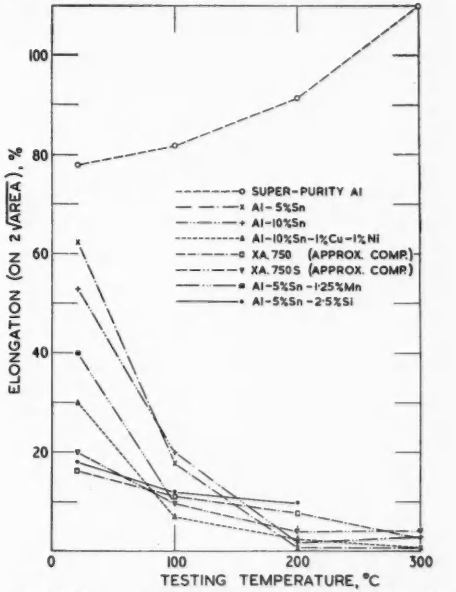

Fig. 6. **Variation with temperature of elongation of various aluminium-tin alloys in the as-cast condition.**

Fig. 7. **Photomicrograph of a cast Al—10% Sn alloy fatigue-test specimen, showing the commencement of fatigue fracture along tin film. (× 150)**

increase hardness and fatigue strength, as shown in Table I.

For comparison, the fatigue strength of a typical tin-base babbitt may be taken as about ± 4000 psi at room temperature and ± 2000 psi at 100° C, with a hardness at room temperature of about 25 VPN. Fatigue strength at 150° C is likely to be very much lower. The advantage of adding copper to the aluminium-tin alloys is that the materials are capable of being hardened by heat treatment. For example, a

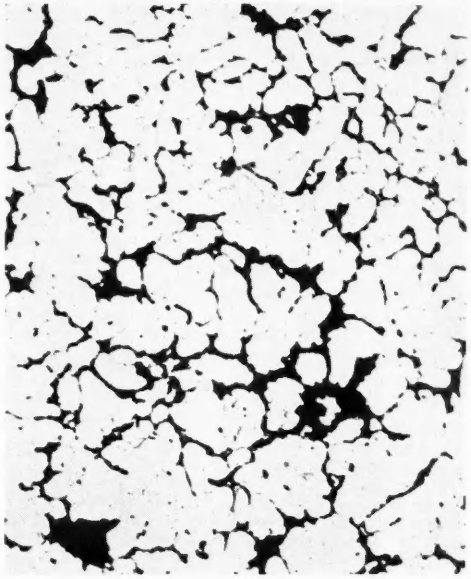

Fig. 8. **Photomicrograph of Al—3%Cu—30%Sn alloy, showing continuous films of tin. (× 150)**

TABLE I. FATIGUE TESTS ON ALUMINIUM-BASE ALLOYS CONTAINING 30% TIN.

Composition of Alloy	Treatment	Testing Temperature, °C	Fatigue Strength, psi	Vickers Hardness
70% Al—30% Sn	Cold-worked and annealed for 1 hr at 350° C	20	±3500	22
		150	±3000	—[a]
69% Al—30% Sn—1% Cu	Cold-worked, heat-treated for 1 hr at 500° C, quenched, and aged for 16 hr at 165° C	20	±6500	27
		150	±4600	—
67% Al—30% Sn—3% Cu	Cold-worked and annealed for 1 hr at 350° C	20	±7100	37
		150	±4600	—
67% Al—30% Sn—3% Cu	Cold-worked, heat-treated for 1 hr at 500° C, quenched, and aged for 16 hr at 165° C	20	±9800	80
		150	±5400	—

binary aluminium—3% copper alloy, if annealed at 500° C and quenched, remains comparatively soft at room temperature, but can be hardened very considerably by ageing at about 165° C for about 24 hr. At still lower temperatures, ageing may take place over an extended period, and the aluminium-tin-copper alloys offer the possibility of providing a bearing which starts off in a relatively soft condition as solution heat-treated, and which gradually hardens at its operating temperature, provided that this is in the region of 100° to 150° C. These hardening processes at such relatively low temperatures may take several weeks and, by adjusting the composition, can be made to reach a maximum after a given number of hours of operation at a given temperature.

Aluminium-tin bearings have applications wherever tin-base babbitt bearings are inadequate from the point of view of load-carrying capacity or fatigue strength, particularly at slightly elevated temperatures. The load-carrying capacity and fatigue strength of the aluminium-tin alloys can be higher than those of the copper-lead alloys, and they are capable of being produced in a wide range of compositions and heat treatment to give a hardness and load-carrying capacity appropriate to the particular application. The low cost of aluminium per unit volume also enables it to compete commercially with both copper and lead.

BACKED ALUMINIUM-TIN BEARINGS

Although aluminium-tin bearings have adequate mechanical properties to enable them to be used in solid form, current automotive practice has been built up largely on backed bearings, and the techniques of manufacture and fitting of such bearings have been so highly developed that it seems likely that in future any new bearing material will have to be capable of bonding

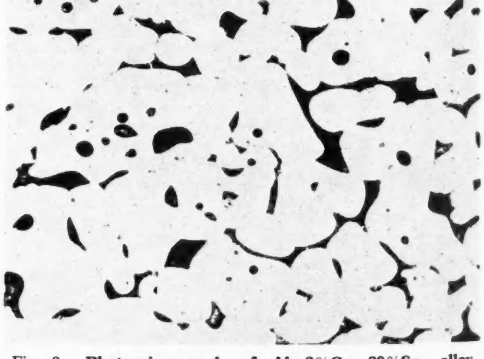

Fig. 9. **Photomicrograph of Al—3%Cu—30%Sn alloy, cold-worked and heat-treated for 1 hour at 500° C, showing a redistribution of tin as discontinuous globules. (× 180)**

to steel or other high-strength backing material. Considerable development work has been carried out by the Tin Research Institute in collaboration with a manufacturer on methods of bonding these alloys to steel by rolling, and some very successful bearings have been produced. It is understood that practical trials of these and of solid aluminium-tin bearings have been going on for two or three years and that the results are highly satisfactory. It has also been shown that it is possible to back aluminium-tin bearing alloys satisfactorily with higher-strength aluminium alloys. This may be particularly useful in cases where the bearing must fit into aluminium-alloy housings.

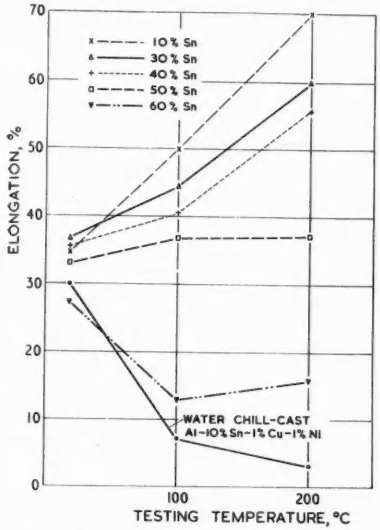

Fig. 10. **Elongation at different temperatures of alloys with an Al/Cu ratio of 98·2, and containing various amounts of tin.**

In backing aluminium-tin alloys to steel, certain fundamental obstacles must be overcome. Since the alloy contains a constituent which is molten at temperatures over 229° C, it follows that no deformation or load can be applied at temperatures above this point. All rolling and working, therefore, must be done at low temperatures, and it is, of course, impossible to carry out any heat treatment at temperatures in excess of the melting point of the aluminium matrix. This means, in effect, that no substantial reduction in the hardness of the cold-worked steel can be achieved after the application of the aluminium-tin alloy. It is also important to avoid the formation at the aluminium-steel interface of a brittle aluminium-tin compound. It has, in fact, been found almost impossible to bond aluminium-tin alloys directly to steel, and intermediate bonds using tin-free alloys have had to be used. This difficulty, although a nuisance to manufacturers of backed bearings, is a useful indication of the intrinsic suitability of aluminium-tin alloys for working against steel shafts.

With the solution of the problem of manufacture of backed bearings, the future of aluminium-tin bearings seems assured.

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Finishes for Aluminium

(*Concluded from page 247*)

One use of plating is to aid in the soldering of aluminium, since copper plating provides a satisfactory surface for soldering. Another application is the silver plating of contact surfaces on electrical components where a very low resistance is vital. Whilst the conventional nickel-chromium plating of aluminium is possible, the corrosion resistance of this coating is not high and, where a bright finish is required, bright anodising will give a far superior performance. Plating of castings, which at present are not readily bright-anodised, is practical where they are not subject to exposure in contaminated environments.

Hard Chromium Plating :—

The most striking advance in plating has been the development of production methods for hard chromium plating. In Germany hard-chromium-plated aluminium cylinders have become standard items for air-cooled engines such as the Porsche and Gutbrod. In all, the output of such cylinders has now reached several hundred thousand. In Great Britain no such great application has been found but hard-chromium-plated cylinders have been standard for several small air-cooled internal combustion engines.

The advantages of hard chromium plating are improved performance and longer life. Tests carried out in Germany showed that, by replacing a cast-iron cylinder with plated aluminium, the compression ratio could be increased from 5·8 to 6·4 with the same knock point, whilst the useful output was increased by 6 to 10% and fuel consumption reduced by a similar amount. Tests have been made in England and similar improvements obtained, whilst wear after 50,000 miles running has proved negligible. German experiments with water-cooled diesel engines have shown that hard chromium plating reduces cylinder and piston temperatures.

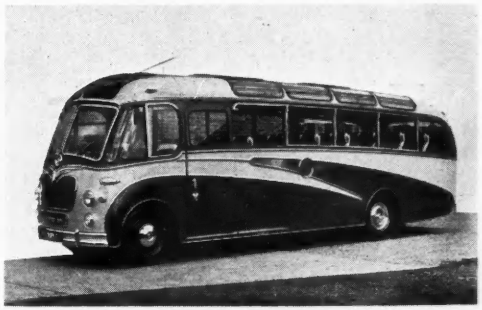

Fig. 3. **Motor coach with electro-brightened and anodised super-purity aluminium-magnesium alloy trim.**
(Courtesy of Duple Motor Bodies Ltd.)

From the above it can be seen that aluminium is a metal with which it is easy to obtain attractive finishes (Fig. 3) quite economically, whilst the high corrosion resistance of most aluminium alloys and the absence of any surface scale akin to rust make it easy to provide effective protection even in the most severe environments. On the other hand, the development of bright-anodised finishes at an economical price may well result in a substantial move away from nickel-chromium plating, especially over brass. Wear-resistant surfaces provided by hard anodising or hard chromium plating are but relatively new developments whose application must inevitably widen in the near future. Other processes are just emerging from the laboratory, although they may have more limited applications. This range of finishes will certainly make an important contribution to widening the field of application for aluminium.

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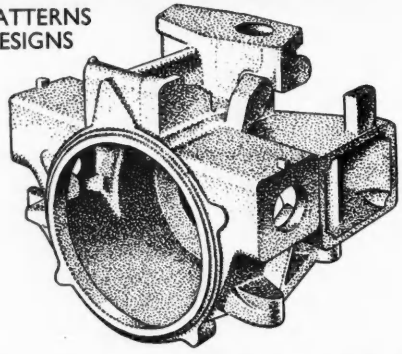

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The Liability to Fatigue Failure of Aluminium-Alloy Structures

By Tibor Haas, Dipl.Ing., A.M.I.Mech.E., A.F.R.Ae.S.*

In any appraisal of an engineering metal, a knowledge of its static strength is the first consideration. Aluminium and its alloys are no exception. Static strength refers here to a single and relatively short-time loading.

It is, of course, common knowledge that, unlike most steels, aluminium alloys do not exhibit a sharply defined elastic limit, yield point, or limit of proportionality in their stress-strain relationship. The departure from the straight line of proportionality is gradual and, instead of a yield point, the stress at which the stress-strain curve departs from the straight line of proportionality by an amount equal to an arbitrary percentage of the gauge length is taken as the proof stress. Thus, for example, a 0·1% proof stress designates the stress at which the permanent set amounts to 0·1%.

The structural engineer, in his constant search for a sound strength criterion, has made good use of proof stress as an indication of the permissible working limit of the material. As with steel, where the ratio of yield stress to static ultimate tensile stress is important, with aluminium alloys the ratio of proof stress to ultimate stress is of increasing significance. If the ultimate strength increases without proportionate increase in proof stress, not much advantage can be gained from it by the designer. As will be seen later, this does not apply to the more recently developed aluminium alloys.

The unexpected failure in actual service of some light alloys with otherwise good mechanical properties has in recent years necessitated intensive research into the effect of static and dynamic long-time loading. The static endurance or creep strength of light alloys is generally defined as a stress associated with a steady creep rate of not more than 10^{-5} inch/inch/day. It would appear that, at room temperature, properly heat-treated aluminium alloys fulfil the requirements so far stipulated by designers, but, unlike steel, their creep strength rapidly decreases with increasing temperature. Of the phenomena observed under dynamic long-time loading, only that known as fatigue need be discussed at any length, as "impact fatigue" is of little importance in the case of light alloys.

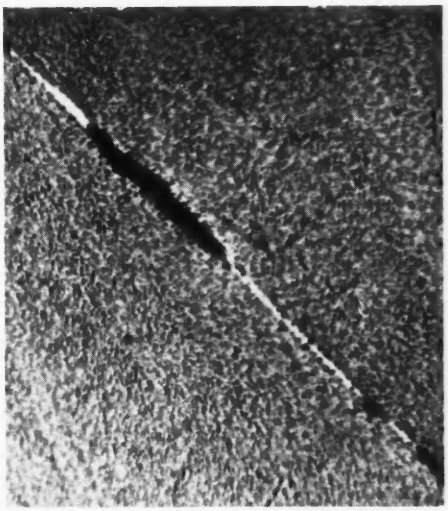
Metallurgical and Engineering Aspects of Fatigue

The problem of fatigue has been present for over a century and, ever since it first appeared, engineers and designers have been curious about its effects, while metallurgists have been more concerned with its causes. Investigations into metallographic structure with the aid of powerful optical microscopes and, lately, with the electron microscope, and the explanations of the mechanism of fatigue by metallurgists are extremely interesting. On his past record, however, it seemed mistaken to look to the metallurgist for a solution of the fatigue problem. In other words, it was considered unlikely that the metallurgist should gain control over the fatigue properties of, at any rate, aluminium alloys. Nevertheless, he has often, quite wrongly, been made a scapegoat for the occasional lack of understanding on the part of engineers of how to avoid failure of machinery components or of structures in actual service. Such failures can be calamitous or merely unpleasant, and accordingly receive attention not only in specialist circles. Thus, the recent fatal accidents to Comet aircraft and the subsequent enquiry have highlighted the phenomenon of fatigue.

Naturally, after such highly publicized accidents as these, the question inevitably arose as to whether the engineer or the metallurgist was to blame. The answer really should be that the metallurgist should respond to the need for the improvement of the fatigue properties of the material, while the engineer should be responsible for its utilization, no matter how good or bad it may be.

Quite recently, there seems to be renewed hope that the metallurgist may be able to bring about further important advances. As reported by Sir Arnold Hall, Director of the Royal Aircraft Establishment, Farnborough, in his recent lecture,[1] some interesting discoveries have lately been made at the R.A.E. while working on the fatigue of aluminium alloys and "this has led us to a tentative theory of the origins of fatigue

* Head of Fatigue Laboratory, Aircraft Division, The Bristol Aeroplane Co., Ltd., Filton.



Figs. 1 and 2. **Photomicrographs of an Al alloy containing 4% Cu, showing** (left) **exudation between slip bands, and** (right) **a crack proceeding along a region weakened by exudation.** (× 1500)
(Courtesy of The Institute of Transport, London).

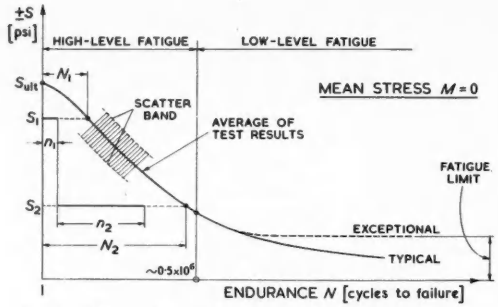


Fig. 3. **Schematic *S-N* curve for aluminium alloys.**

which may help toward the development of alloys of improved properties.

"We have vibrated small polished specimens electromagnetically, and made microscopical examinations of them. We have found that, under repeated loading within the elastic limit as ordinarily understood, slip occurs in the crystals of the material.

"We have been able to observe a number of metallurgical changes taking place in the alloy before fatigue cracking occurs. One of these is the exudation of thin metallic ribbon from the crystal surfaces. . . ." Sir Arnold showed a photomicrograph (Fig. 1) illustrating exudation between slip-bands in an Al alloy containing 4% Cu. These metallic ribbons could be seen leaving a crevice in the surface, which in a further photomicrograph (Fig. 2) was shown as a crack proceeding along such a region weakened by exudation.

Quoting Sir Arnold further:—"It is well known that, in aluminium alloys, high temperature promotes precipitation of the alloying atoms and produces a soft matrix of practically pure aluminium in which are embedded large aggregates of the precipitates. One explanation of the exudation phenomenon induced by repeated loading is that the slip produced in the crystals causes local high temperatures, which in turn cause local precipitation of the alloying atoms. The soft spots so produced are then extruded under the action of the alternating stress, and the crevice is formed, causing stress concentrations, which excite the phenomenon further, so extending the crevice, which eventually becomes a fatigue crack.

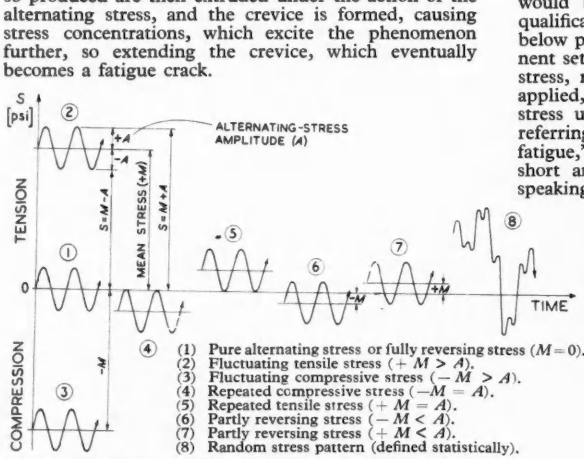

S [psi]
ALTERNATING-STRESS AMPLITUDE (A)
TENSION
MEAN STRESS (+M)
S=M-A
S=M+A
TIME
COMPRESSION
(1) Pure alternating stress or fully reversing stress ($M=0$).
(2) Fluctuating tensile stress ($+M > A$).
(3) Fluctuating compressive stress ($-M > A$).
(4) Repeated compressive stress ($-M = A$).
(5) Repeated tensile stress ($+M = A$).
(6) Partly reversing stress ($-M < A$).
(7) Partly reversing stress ($+M < A$).
(8) Random stress pattern (defined statistically).

Fig. 4. **Definition of cyclic and random stress patterns.**

"If this explanation be correct, a higher fatigue resistance could result, were it possible to choose alloying constituents which will not precipitate under these circumstances."

So much for the metallurgical aspect of fatigue. Apart from being a general scientific problem, fatigue is a material property; as such, it is basic to engineering. The additional aspects which enter into the fatigue problem through material being employed in various shapes, to fulfil diverse functions under varying conditions, are often referred to as "structural fatigue."

The *S-N* Curve

In this necessarily brief review of the problem, it is thought that the engineer's approach and the position aluminium alloys occupy should be outlined. To begin with, the basic criterion of metallic performance is expressed by the *S-N* curve, i.e., a plot of failing stress against endurance, the latter signifying the number of stress reversals that can be endured by the metal up to and including failure.

Fig. 3 shows a schematic *S-N* curve and gives a number of the terms which will be used in the following. Attention is particularly drawn to the scatter band, signifying upper and lower boundaries, within which test points are situated. Endurances at one stress level may vary as much as one to nine, although generally one to three is a more frequent ratio. Test results plotted in *S-N* diagrams show the average curve, though, without showing test points or stating a measure of scatter, the information would be incomplete. Another statement is required for complete definition, and this concerns the magnitude of the mean stress, though, of course, other alternatives are possible and are frequently used. The mean stress M can be visualized as a static stress, superimposed on which there is an alternating stress of amplitude A. The limits of cyclic stress of constant amplitude at a given mean stress are defined by $S = M \pm A$; this equation also describes the cycle adequately. Generally, the *S-N* diagram is a plot of A against N, with M as a parameter. In Fig. 3, the mean stress is stated to be zero; this cyclic-stress pattern is shown as case (1) in Fig. 4, where also all the other basic stress patterns are illustrated.

Fatigue failures generally occur quite suddenly and without prior indication, since the plastic deformation involved is generally very small. The case of static failure is represented on the *S-N* curve by the stress corresponding to an endurance equal to unity. Any steady stress below the static ultimate tensile stress would be endured indefinitely (subject only to the qualifications implied by creep); also, if the stress is below proof, it is sustained without appreciable permanent set. It is generally true to say that the higher the stress, relative to the static ultimate stress repeatedly applied, the lower is the number of applications of that stress under which failure by fatigue will occur. In referring to "high-level fatigue" and "low-level fatigue," the stress levels which are associated with short and long endurances respectively are, broadly speaking, distinguished (Fig. 3).

A definition as to what is considered failure is necessary when evaluating tests or inspecting parts in service, because incipient cracks generally form long before they become large enough to cause visible failure. Their formation may be speeded up or delayed by detrimental (tensile) or favourable (compressive) residual stresses respectively. Residual stresses, i.e., those present in a design member before the applied stress, may be due to cold working or thermal processes inherent in the manufacture. Once these incipient cracks are formed, their propagation depends on whether they run into areas of high or low stress. This is a matter which has been much studied recently, and it appears that crack propagation depends a great deal on the general stress level. The difficulties encountered in reproducing actual conditions experimentally are here formidable, as fatigue-testing machines apply either constant-load cycles or constant-strain cycles. In the

case of constant-load cycles, stress will increase as soon as cracks begin to reduce the cross-sectional area of the specimen, and consequently crack propagation is rapid, while, in the case of constant-strain cycles, cracks cause a load decrease in maintaining the given strain, and therefore propagate slowly. It will be appreciated that these facts have a bearing on the endurance lives of specimens tested in different types of fatigue-testing machines, and also on the appearance of the fracture surfaces. Fig. 5 shows a typical aircraft joint broken in a constant-strain fatigue-testing machine under fluctuating tensile stress. There are bolts and rivets in the joint, the main body of which is an aluminium-alloy extrusion. The fracture surface shows two distinct types of areas, corresponding to the types of failures which have taken place. In the figure an arrow points to the " nucleus " or origin of the fatigue failure, due to stress concentration caused by the rivet hole. The semicircular marking, due to radial spread of the crack, is the boundary of the main fatigue failure. Another nucleus and a more limited radial spread can be observed at the other end of the rivet hole. A smaller fatigue area can be seen at the top of the joint, due to another rivet. The remainder of the fracture is of a static type, extending over an area which was insufficient to carry the applied load. It is of rough, dull appearance and, as is the case with ductile fractures, it is, when seen microscopically, intercrystalline, i.e., the fracture has taken its course along the grain boundaries. The area of the fatigue failure is smooth, velvety, and has shiny facets, which are reflections of light from what is a transcrystalline fracture surface. It has been said that, without the corrosive influences present in air, the fatigue fracture would also be intercrystalline. It should be noted that corrosion is intercrystalline ; the fatigue fracture following corrosion is, however, transcrystalline. Distinctions are made between corrosion fatigue and what is known as stress corrosion. The facts are that fatigue tests made on aluminium alloys in chemically inert atmospheres are likely to throw light on the effects of corrosion. There is some evidence that, in such atmospheres, the *S-N* curves become similar to those of steel, i.e., they exhibit a definite fatigue limit. It should follow that those aluminium alloys which have *S-N* curves of the steel type when tested in air should be corrosion-resistant. This is still a wide field for investigation. As the fracture shown in Fig. 5 was produced in a conventional testing machine, its appearance is typical of fractures produced by cycles of constant amplitude—in this case, to be exact, by cycles of constant strain amplitudes.

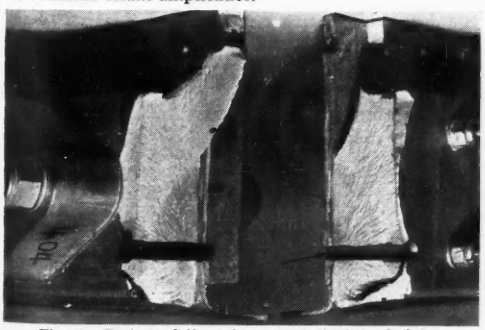


Fig. 5. **Fatigue failure in a typical aircraft joint.**
(Courtesy of the Bristol Aeroplane Co., Ltd.)

However, with the exception of machines which receive cyclic loading, such as engines, turbines, and other high-speed machinery, most structures and mechanisms receive random loading (Fig. 4). Examples of this are in motor cars,[2] aeroplane wings,[3] and bridges.[4] It has become the complex art of the engineer to correlate these loadings with the damage they cause to the structure ; in another words, he is expected to design for a given life under conditions which he can assess only statistically. As statistics enter into the problem, there are variations to be expected, and thus the endurance life of a structure should be looked upon as a probability of occurrence amongst the lives of many other identical structures (the " population "). The phenomenon known as " scatter " can itself be interpreted as a statistical problem ; it refers to the fact that nominally identical specimens under the same type and magnitude of repeated loading often show largely varying endurance lives.[5] It is important to realize the significance of the word " nominally " in this context. The number of variables is so great that, strictly speaking, no two specimens are identical.

The physicist, whose outlook and interest centre on strictly reproducible experiments, has succeeded in producing nearly identical fatigue specimens for his laboratory work, with the result that scatter has become insignificant. However, machine parts and engineering structures are far from such a state of perfection. For one thing, there are ever-present stress raisers or stress concentrations, as a result of which there exist local stresses of several times the magnitude of the applied stress. Broadly speaking, the stress concentrations are due to discontinuities in the cross-section, i.e., the shape of the member, and also to the method of joining, e.g., bolts or rivets. Apart from these inherent stress raisers, there are others due to manufacturing inaccuracies, such as differences in machining or lack of care in assembly.

In the Comet Report of the Court of Inquiry, in the " Note of Metal Fatigue by the Assessors," Professor Murphy, of the University of Birmingham, states in his evidence :—" The prime consideration is, I think, to get the general stress level down, so that you are not in jeopardy in this way. If you can get the general stress level down, you can tolerate the variations which are very liable to happen in practical manufacture. If you have a high stress level, you are setting yourself the task of guarding against most minute variations from the ideal." This is a concise statement of the task of the design engineer, which is difficult to translate into reality if the resulting performance, efficiency, and weight should be compatible with reasonable expectations.

A useful tool for the worker in fatigue was created by Miner, who formulated, in 1945, what is known as the cumulative-damage rule.[6] It opened up a new field of inquiry into the mechanism of damage. Present-day ideas on fatigue cannot well be understood without reference to this rule, and thus it is not considered out of place to restate it here. If W = work done to failure, and w_1 = work done at n_1 cycles at an arbitrary stress level S_1, and N_1 is the endurance at stress level S_1 (a point on the *S-N* curve), then he assumed that

$$w_1/W = n_1/N_1,$$

and $(w_1/W) + (w_2/W) + \ \ldots \ \ldots + (W_m/W) = 1.$

Therefore $(n_1/N_1) + (n_2/N_2) + \ \ldots \ \ldots + (n_m/N_m) = 1.$ (Fig. 3).

This can more simply be written as $\Sigma(n/N) = 1$. However, it was found that the sum of these ratios of cycles applied to cycles to failure could be any value between 0·61 and 1·61, instead of unity. Thus, the rule cannot be indiscriminately employed without experimental verification from case to case.

Now, consider again the conventional *S-N* curve. In the absence of stress concentration (e.g., with smooth, carefully prepared specimens) there is a fairly distinct relationship between the maximum stress which a material will withstand indefinitely under alternating loading and the static ultimate tensile stress S_{ult}. For a wide range of steels the amplitude of this cyclic stress is about $\pm$ 0·45 S_{ult}, and is known as the fatigue limit. For most aluminium alloys there is no such safe limit,

and the fatigue strength must be described in association with an arbitrary endurance, i.e., a given number of cycles to failure (say 50×10^7). An exception among aluminium alloys in this respect is the American aluminium-zinc-copper-magnesium alloy 75 S (which is similar to the British alloys D.T.D. 363A and 683). Its *S-N* curve, due to Oberg,[7] of the Materials Laboratory of the Wright-Patterson U.S. Air Force Base, is plotted in Fig. 6. This alloy can be seen to reach its fatigue limit, 20,200 psi, at about 100 million reversals. It has a proof stress of about 81,200 psi and a static ultimate tensile strength of 91,000 psi; therefore, the ratio of proof stress to ultimate stress is about 0·9, and the fatigue limit is about 22% of the static ultimate stress, as against 45% for many steels. Also plotted for comparison are *S-N* curves for mild steel and for a typical aluminium alloy which has no fatigue limit. In general, the *S-N* curves common to most aluminium alloys are similar in form to those of other non-ferrous metals in that they have no definite fatigue limit. Three more *S-N* curves for aluminium alloys are shown in Fig. 7, of which two are typical, while the third curve, for alloy N7-0, exhibits the exceptional mild-steel form[8]; this latter alloy has a particularly high ratio of fatigue limit to ultimate tensile strength. All the specimens used in the *S-N* curve determinations referred to above were free from stress concentrations, and were tested under pure alternating loading (case (1) in Fig. 4).

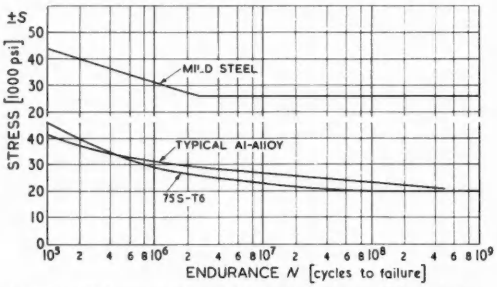


Fig. 6. ***S-N* curves for mild steel and two different aluminium alloys under pure alternating stress.**

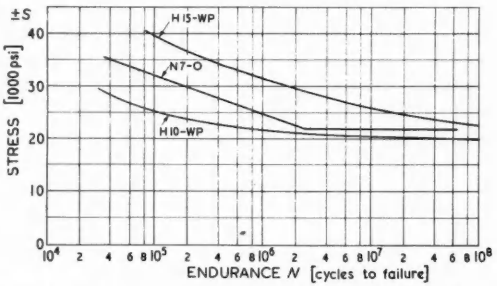


Fig. 7. ***S-N* curves for three different aluminium alloys under pure alternating stress.**

The advent of high-strength alloys such as D.T.D. 363A and D.T.D. 683 introduced features into design considerations which brought fatigue into prominence. The specification values for these alloys called for an approximate proof to ultimate stress ratio of $S_p/S_{ult} = 0{\cdot}85$, but actually this value was generally in excess of 0·90. This means that the range of stress over which no permanent deformation occurs has greatly increased, and thus there is a decrease in the stress range over which permanent deformation without failure can take place.[9] The new materials had increased static strength, lowered ductility, and little or no improvement in fatigue strength. In structures employing aluminium alloys, fatigue was not considered in the past; the absence of fatigue failures, relative to other fields of engineering using different metals, was due to the large safety factors used. By steady improvement in design methods, the factor of safety applied to the strength calculations could be reduced, while simultaneously the static strength of the material increased, unfortunately without commensurate increase in fatigue strength. Fatigue ceased to hide behind the safety factor and came out into the open. As aluminium alloys are extensively used in the precipitation-hardened (age-hardened) state, it is interesting to study, in the light of the above, the changes in mechanical properties arising from precipitation hardening. Consider the aluminium-copper-manganese-magnesium alloy 14 S or D.T.D. 364. The ratios of the precipitation-hardening properties to the original properties are as follows:— Proof stress 4·3, ultimate stress 2·6, fatigue limit (at 50×10^7 cycles) 1·4.[10] While the proof stress has greatly increased and the ultimate stress moderately increased, the fatigue strength has increased only insignificantly.

Prevention of Fatigue by Realistic Testing

From the preceding discussion it will have become clear that, to make full use of the advantages of high-strength aluminium alloys, "design against fatigue" has become part of the engineer's duties. He must necessarily be interested in, and concerned with, such factors as:—

(1) Comprehensive laboratory fatigue tests on the basic material and on the actual components.
(2) Influence of stress concentrations (notch sensitivity) on fatigue life, due to detail design, joining processes, machining, heat treatment, etc.
(3) Effect of corrosion and influence of surface-treatment processes.
(4) Influence of "prestressing," "overstressing," "understressing," and rest periods.
(5) Influence of stress cycles of varying magnitude and cumulative damage.

The culmination of these efforts is the designer's quest for a solution which will enable him to predict the life of his structure or machinery based on simulated operational conditions, as nearly as possible representative of those met with in actual service.

Perhaps the most promising approach to such a solution is afforded to-day by the use of programme-loading fatigue-testing machines.[11] Before going any further, let us recall the cumulative-damage rule already mentioned. This rule, if it held good unconditionally, would provide a reasonable chance of determining the endurance life of design members under varying loading conditions. However, the cumulative-damage rule makes no statement as to the temporal sequence of stress cycles of varying amplitude, although it is a well-known fact that the effect of varying sequence is by no means negligible. For instance, if a design member is first subjected to stress cycles below its normal fatigue limit and then tested at higher stress cycles, it will generally show an improvement in fatigue life. This is known as understressing. Similarly, overstressing refers to loading a design member above its normal fatigue limit for a relatively large number of cycles before loading it at another stress level. This reduces life, although only a few high-stress applications prior to retesting, known as prestressing, generally improve endurance. Apparently, the mechanism of damage is different at different stress levels, and damage is not uniform, as assumed by the cumulative-damage rule.

Here, the programme-loading machine is likely to bridge the gap. In order to obtain a realistic expectancy of fatigue life under conditions of random loading (case (8), Fig. 4), the latter must first be recorded[2, 3] over a sufficient length of time to yield a statistical load-frequency distribution, known as the "load spectrum."

By suitably reducing the frequency scale of the latter, and re-grouping the cyclic loads into a descending-ascending order, the programme cycle is obtained, which is then repeatedly reproduced by the testing machine until failure of the specimen.[11] The number of programme cycles to failure multiplied by whatever one such cycle represents, e.g., hours of service or miles of travel, gives the endurance of the test specimen.

Not only does the thorough mixing of loads at all levels tend to eliminate the various errors present in the evaluation of endurance under conditions of random loading from tests at a constant level, but it also produces a different appearance of the fracture. It was always hoped that, if laboratory fractures closely resembling service fractures could be produced, the fatigue problem would be one step nearer to its solution. At any rate, the fracture in Fig. 8, obtained in a programme-loading fatigue-testing machine, permits a more thorough study of crack propagation than was hitherto possible. The specimen was a motor-car stub axle[11] of heat-treated alloy steel of 128,000 psi ultimate tensile strength, and was loaded in pure alternating bending. As can be seen, each programme cycle (consisting of $0{\cdot}5 \times 10^6$ reversals) left its individual mark in the fracture surface, and each increment in crack depth can therefore be expressed in terms of cycles. Further consideration of this fracture shows that each programme cycle has produced three crack bands. The thin dark band is due to the highest loads in the cycle, followed by a wider, less dark band, due to somewhat lesser loads, but still above the fatigue limit. The bright band corresponds to loads below the fatigue limit. Seen macroscopically, the dark bands show a shear-type fracture and the bright band a cleavage-type fracture.

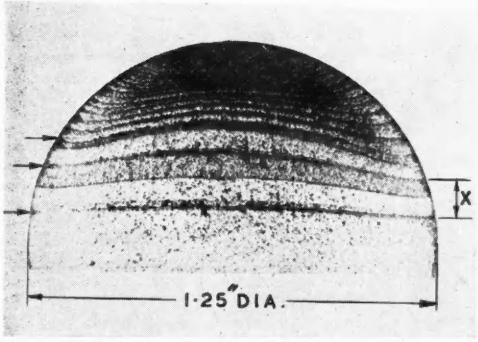


Fig. 8. **Appearance of fracture obtained in a programme-loading fatigue-testing machine.**

The arrows indicate fractures caused by the highest loads in each consecutive programme cycle.

(×) Crack propagation due to all loads within one programme cycle.

(Courtesy Dr. E. Gassner).

Although the above-mentioned method of testing was applied to a steel design member, all that has been said is generally valid for most engineering materials and many engineering applications. However, the significance of this test method is perhaps greater for aluminium alloys than for steels. The reason for this lies in the fact that aluminium alloys do not follow Hooke's law. In their stress-strain relationship, some exhibit a more or less sudden change, often referred to as the double modulus. Such metals, at a slow cyclic speed of between one and seventy cycles per minute, which is about the rate of loading in a number of service applications, already undergo plastic deformation, and therefore, particularly at high loads, realistic fatigue testing stipulates fatigue machines with low-speed drives. Fortunately, as load spectra show, these higher loads are sufficiently infrequent, so that the testing time in programme-loading machines with combined slow and fast drives, using the fast drive for the lower loads, is not unduly prolonged. This digression into testing-machine requirements is necessary to show that new ideas in this field must be employed, if more rational designs in aluminium alloys are to be evolved.

Method of Joining

Brief mention should be made of the position aluminium alloys occupy with respect to joining methods, because, as has been shown, the fatigue strength of a structure should not be looked upon as something basic to the material, but rather as that of the material afflicted by joints. This affliction, of course, is the stress concentration inherent to varying degrees in any joint.

With regard to welded joints, great progress has been made in recent years in arc welding, with the object of making the joint equal to the static strength of the parent metal. If this object and the improvement in the fatigue endurance of the joint have not quite been achieved to-date, the considerable research and development work under way may produce the desired results in the course of time.

Although better results have been achieved with resistance spot welding and seam welding, riveting still occupies the most important place as a joining method. Most of the experience in riveting aluminium alloys has been gained on aircraft construction[12]; indeed, the development of aluminium alloys is closely linked with that of aircraft. On the other hand, recent progress in building bridges entirely of aluminium alloys has led to the successful employment of aluminium rivets up to one inch in diameter.

In bolted joints, methods of deliberately inducing favourable residual stresses have led to higher fatigue resistance than was previously obtainable.

Metal-to-metal joints by bonding methods with synthetic resins, such as "Redux,"[13] show up well from the fatigue point of view, and have certainly come to stay.

Acknowledgment :—

The author is indebted to the Bristol Aeroplane Co., Ltd. for permission to publish this paper; however, the views expressed are personal and not necessarily those of the Company.

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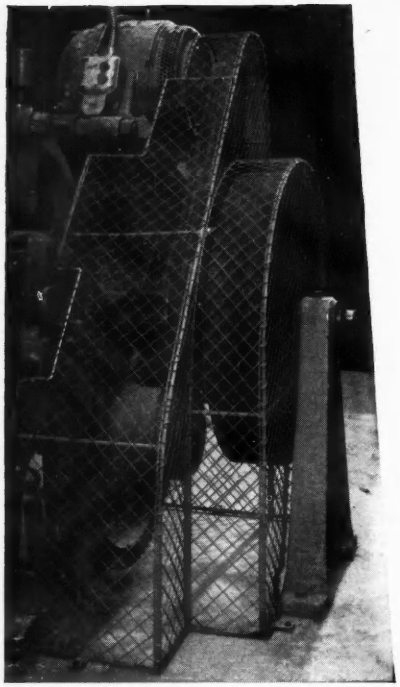

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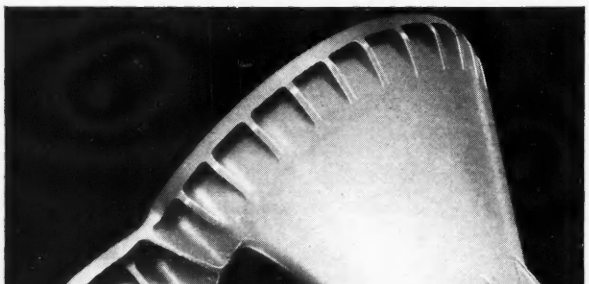

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NEWS OF THE MONTH

PERSONAL

Mr. Frank Banfield, general manager, has been appointed managing director of The Expanded Metal Co. Ltd., Burwood House, Caxton Street, London, S.W.1, in succession to **Lieut.-Commander G. C. Hans Hamilton,** who will continue as chairman of the company.

Mr. E. J. Batchelor has been appointed general manager of the Automobile Division of the David Brown Corporation Ltd.

Mr. H. H. Begent, M.I.E.E., has rejoined the English Electric Co. Ltd. and has been appointed deputy sales manager of the Transformer Department, Stafford.

Mr. C. F. Bolton has been appointed consulting engineer to the English Salvi Co. Ltd., 11 Kensington Church Street, London, W.8.

Viscount Bracken, P.C., the Hon. Alexander Hood, Sir Eric Speed, K.C.B., K.B.E., M.C., and **General Sir William Morgan, G.C.B., D.S.O., M.C.,** have been elected to the Board of Associated Electrical Industries Ltd.

Mr. J. H. Cansdale, M.I.E.E., deputy manager of the traction department of British Thomson-Houston Co. Ltd., Rugby, will be responsible for all contracts, and **Mr. M. W. T. Rees, B.Sc.(Eng.), A.M.I.E.E., Assoc.I.Mech.E.,** has been appointed assistant manager (projects) of the traction department.

Dr. Horace W. Clarke, F.I.M., chairman and managing director of James Booth & Co. Ltd., Birmingham 7, has been elected President, and the **Hon. Geoffrey Cunliffe,** deputy chairman and managing director of the British Aluminium Co. Ltd., Norfolk House, St. James's Square, London, S.W.1, has been elected vice-president of the Aluminium Development Association.

Mr. A. R. Collie has been appointed sub-contracts officer of the Westland Aircraft Ltd., Yeovil, Somerset.

Mr. W. J. M. Cook, F.R.I.C., has been appointed to take charge of the Industrial Sales Division of Patterson Engineering Co. Ltd., Windsor House, Kingsway, London, W.C.2.

Mr. Roger Gresham Cooke, C.B.E., M.P., has been elected to the Board of Kerry's (Great Britain) Ltd., Warton Road, Stratford, London, E.15.

Dr. J. Craik, M.A., B.Sc.(St. Andrews), has been elected chairman of the Nobel Division of Imperial Chemical Industries Ltd., in succession to **Dr. W. J. Jenkins,** who has retired from the Company's service.

Mr. E. G. Crossling has been appointed manager of the Coventry Works of the British Thomson-Houston Co. Ltd., in succession to **Mr. H. J. Armstrong,** who has retired.

Mr. H. G. Davis, B.Sc., has been appointed works manager at the Plymouth Works of Acheson Colloids Ltd., 18 Pall Mall, London, S.W.1. **Mr. J. B. MacLean, B.A.,** has joined the export department, and **Mr. G. C. B. Andrew** has been appointed publicity officer of the company.

Mr. George T. Deck, technical director of the American Potash & Chemical Corporation's main plant at Trona, California, has been appointed plant manager of the new American Lithium Chemicals Inc., plant near San Antonio, Texas.

Mr. R. J. Dixon, A.M.I.P.E., chief engineer and a special director of Wickman Ltd., Banner Lane, Tile Hill, Coventry, has been elected to the Board of the company.

Mr. T. P. Douglas, M.B.E., has been appointed engineer-in-charge of the Sutton Coldfield Television Transmitting Station of the British Broadcasting Corporation.

Mr. D. K. Fraser, formerly works manager of the electrical machines division of Brush Electrical Engineering Co. Ltd., Loughborough, has been appointed director and general manager of Petters Ltd., Staines, Middlesex. **Captain R. C. Petter** has resigned his appointment as managing director, but remains a non-executive member of the Board and also of the Board of the parent company, The Brush Group Ltd.

Mr. J. E. Gamage and **Mr. J. R. Spanswick** have been elected to the Board of the Electric Furnace Co. Ltd., Netherby, Weybridge, Surrey. **Mr. E. F. Watson** has been elected a director of the Electric Resistance Furnace Co. Ltd.

Mr. George Hallewell, M.I.Mech.E., chief engineer to the company for the past twenty years, has been elected a director of Blackstone & Co. Ltd., Stamford, Lincolnshire.

Sir Graham Hayman has been elected President of the Federation of British Industries, 21 Tothill Street, London, S.W.1, in succession to **Sir Harry Pilkington,** who has held office for two years.

Mr. F. A. Hurst, chairman and managing director of Samuel Osborn & Co. Ltd., Clyde Steel Works, Sheffield 3, has been elected President of the Sheffield Chamber of Commerce.

Mr. P. L. Jones, M.C., B.Sc., M.I.C.E., M.I.Mech.E., Wh.Ex., M.I.Mar.E., director of Swan, Hunter and Wigham Richardson Ltd., Newcastle-on-Tyne, and the Wallsend Slipway and Engineering Co. Ltd., has been re-elected President of the North-East Coast Institution of Engineers and Shipbuilders, Bolbec Hall, Newcastle-on-Tyne 1.

Mr. W. N. Kilner, M.I.E.E., has been appointed chief engineer of the newly formed turbo-generator engineering department of Metropolitan-Vickers Electrical Co. Ltd., Trafford Park, Manchester 17. **Mr. C. P. Holder, B.A., M.I.E.E.,** has been appointed assistant chief engineer of the plant department, and **Mr. E. Nicholson, M.B.E., T.D., B.Sc., A.M.I.E.E.,** has been appointed assistant chief engineer of the switchgear department.

Mr. F. A. King and **Mr. A. J. Hughes** have retired from the Board of Kelvin & Hughes Ltd., after some 60 years of service to the company. **Mr. F. W. Bates,** general works manager, has been elected a director of the company.

Mr. E. D. Knights, B.Sc.(Lond.), F.I.M., research metallurgist of British Railways, Derby, has been elected President of the East Midlands Metallurgical Society, in succession to **Dr. H. K. M. Lloyd, B.Sc.,** Professor of Metallurgy, University of Nottingham.

Sir Leonard Lord, K.B.E., chairman and managing director of The British Motor Corporation, has been elected President of the Institution of Production Engineers, 10 Chesterfield Street, London, W.1. **Mr. G. Ronald Pryor,** chairman and managing director of Edward Pryor & Son Ltd., Sheffield, has been elected chairman of Council, and **Mr. H. G. Gregory,** manager of the Northern Factories of Fairey Aviation Co. Ltd., Stockport, has been elected vice-chairman of Council.

Mr. T. A. Mason, M.A., B.Sc., works manager of A. Boake, Roberts & Co. Ltd., Carpenters Road, London, E.15, has been elected to the Board of the company and of the parent company, A. Boake, Roberts & Co. (Holding) Ltd.

Mr. D. W. L. Menzies, managing director of Bonnington Castings Ltd., Leith, and director of several other companies, has joined the Board of Sigmund Pumps Ltd., Team Valley, Gateshead 11.

Sir Percy H. Mills, Bt., K.B.E., has joined the Board of Lancashire Dynamo Holdings Ltd. **Mr. J. G. Shaw** has resigned from the Board, but remains a director of some companies of the Lancashire Dynamo Group.

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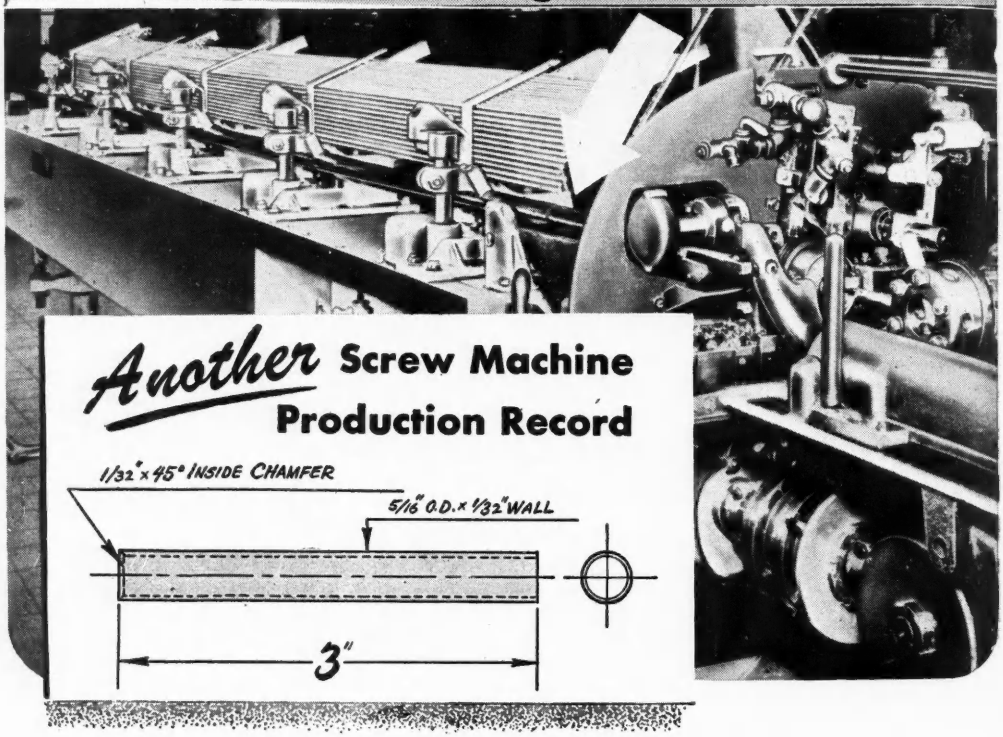

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Mr. **J. W. Moore** has been appointed general manager of Silentbloc Ltd., Manor Royal, Crawley, Sussex.

Mr. **D. P. Ransome,** managing director of E. H. Bentall & Co. Ltd., Maldon, Essex, has been elected President of the Agricultural Engineers Association.

Mr. **A. F. Rayner** and **Mr. R. C. Holt** have been appointed joint managing directors of the Anti-Attrition Co. Ltd., Woodlands Park Works, Maidenhead, Berks.

Mr. **Erik Ryd** has been appointed technical director in charge of design, research and development of the Atlas Diesel A.B., Stockholm. **Mr. J. A. Perham, B.Eng., M.C.I.M.M.,** who was managing director of the British company since 1952, has been appointed sales director. **Mr. J. C. Greig,** formerly manager of the stationary compressor division, has been appointed managing director of Atlas Diesel Co. Ltd., Beresford Avenue, Wembley, Middlesex.

Mr. **C. Ryder, M.I.E.E.,** has been appointed chief engineer of the Instrument and Meter Department of Metropolitan-Vickers Electrical Co. Ltd., Trafford Park, Manchester 17, in succession to **Mr. T. W. Ross, M.I.E.E.,** who has been appointed consultant to the chief electrical engineer of the company. **Mr. J. C. Dawson, B.Sc., A.M.I.E.E.,** has been appointed assistant sales manager of the Switchgear Department.

Professor M. Stacey, D.Sc., F.R.S., and **Sir Alexander Todd, M.A., D.Sc., F.R.S.,** have been elected vice-presidents, and **Professor F. Bergel, D.Sc., F.R.I.C.,** honorary secretary of the Chemical Society, Burlington House, London, W.1.

Mr. **C. J. Tanner** has been appointed general manager of Solex (Gauges) Ltd., 72 Chiswick High Road, London, W.4.

Mr. **C. D. H. Webb,** executive director of the Plessey Co. Ltd., Ilford, Essex, has been elected a director of Plessey International Ltd.

Mr. **A. M. Worswick, A.M.I.Mech.E.,** formerly chief designer of the Press Division of Foster, Yates & Thom Ltd., has been appointed chief engineer of Towler Bros. (Patents) Ltd., Electraulic Works, Rodley, Leeds.

INTERNATIONAL CONFERENCE ON FATIGUE OF METALS

The Council of the Institution of Mechanical Engineers are arranging an International Conference on Fatigue of Metals to be held from Monday 10th September to Friday 14th September 1956, inclusive. Sessions for the delivery of papers will be held daily from 10.00 a.m. to 12.30 p.m. and from 2.30 p.m. to 5.30 p.m.

It is hoped to obtain up to sixty papers covering the whole field, and these will be divided into groups, the papers in the various groups being presented for discussion in abstract form by Reporters.

The Presentation of the papers will be preceded by an address reviewing the field of knowledge of fatigue. The address will be presented by Dr. H. J. Gough, C.B., M.B.E., F.R.S., a Past-President and Honorary Member of the Institution.

THE PRODUCTION EXHIBITION, LONDON, 1956

The second Production Exhibition and Conference will be held in the Grand Hall, Olympia, London, from the 23rd to the 31st May, 1956.

The Exhibition will be selective in as much as exhibitors will show only methods by which production can be increased, or ways in which they have themselves improved production in their own planning or in other firms' factories. It will show the achievements of British industry in production techniques and its theme will be the proper use of the great, but as yet partially used, resources which can accelerate Productivity.

The Exhibition will again be held in conjunction with the Conference of the Institution of Production Engineers, which is attended by production experts from every industrial field. The first Exhibition attracted much interest overseas and was attended by many foreign visitors. In 1956 many more foreign visitors will visit the Exhibition and world-wide publicity will be given to it.

The 1955 Conference which has been announced by the Institution of Production Engineers is based on the important topic of the automatic factory and automation will form an important section of the 1956 Production Exhibition.

All enquiries regarding the 1956 Exhibition should be made to S. D. Cooke, The Production Exhibition, Andry Montgomery Ltd., 11 Avenue Chambers, 4 Vernon Place, London, W.C.1. Tel.: CHAncery 2223/7.

BUSINESS NOTES

Thurgar Bolle' (Successors) Ltd. announce that their head office has been removed from Wellingborough to Orient House, Field Street, Kettering, Northants. Tel. No.: Kettering 3672.

The Hoyt Metal Company of Great Britain Ltd., Deodar Road, London, S.W.15, announce that their subsidiary company has changed its name to Hoyt Metal Company of Australia Pty. Ltd. The new factory at 68/80 Hughes Avenue, Ermington, N.S.W., Australia, is now in full production.

The British Oxygen Company Ltd. announce major changes that are to take place in the structure of the company and its subsidiaries. The re-organisation plan will be put into operation as from October 1, 1955.

A new operating subsidiary company, British Oxygen Gases Ltd., will be formed with a first authorised share capital of £15 million to undertake all trading operations in industrial and medical gases and equipment which are now conducted in the name of the parent company. The Board of British Oxygen Gases Ltd. will consist of Mr. T. E. Potts, chairman, Mr. M. K. Arnott, commercial director, Mr. N. L. G. Lingwood, marketing director, Mr. G. W. Lake, production director, Mr. R. C. Hesketh-Jones, sales director (Industrial Division), Mr. F. W. B. Kittel, sales director (Medical Division) and Mr. H. Coburn, director and secretary.

The chemical interests will be brought into another new subsidiary, British Oxygen Chemicals Ltd.

Mr. T. E. Potts, managing director of African Oxygen and Acetylene (Pty.) Ltd., and Mr. J. Strong, managing director of Quasi-Arc Co. Ltd. and Fusarc Ltd., have been elected to the Board of the parent company and will assume responsibilities in the new main subsidiary companies.

Arrangements are also in hand for the grouping of B.O.C. interests in electrode manufacture and electric welding processes, including the activities of the Quasi-Arc and Fusarc companies.

Besson & Robinson Ltd. announce that they have now moved from Kidbrooke to a new 25,000 sq. ft. factory at East Industrial Estate, Harlow, Essex. Tel. No.: Harlow 25231/4.

The National Smoke Abatement Society has moved to new offices at Palace Chambers, Bridge Street, London, S.W.1. Tel. No.: TRAfalgar 6838/9.

B.S.A. Tools Ltd. announce the formation of a separate Small Tool Export Department at their Sparkbrook factory. Mr. E. J. Abbey has been appointed export manager and Mr. J. D. Willcock is now designated assistant export manager of the Small Tools Division, whose address is P.O. Box 232, Montgomery Street, Birmingham 11. Export sales of machine tools will continue to be dealt with at Mackadown Lane, Kitts Green, Birmingham 33, under the supervision of Mr. P. B. Hugman, export manager of the machine tools division.

Monks & Crane Ltd., Birmingham, have opened a new branch office at 23 Dean Street, Newcastle-upon-Tyne. Mr. John Coe is responsible for the office and stock control, and Mr. K. Keighley is the representative for the area.

Borax Consolidated Ltd. have moved to Borax House, Carlisle Place, London, S.W.1. Tel. No.: VICtoria 9070.

Bennis Combustion Ltd., Little Hulton, Walkden, Manchester, announce that, following on an agreement with Todd Oil Burners Ltd., 130 Leadenhall Street, London, E.C.3, an associate company of Todd Shipyard Corporation, New York, N.Y., U.S.A., they are now able to execute complete oil-burning installations for shell-type and water-tube boilers. The British-manufactured burners incorporate latest American developments in fuel oil-burning technique.

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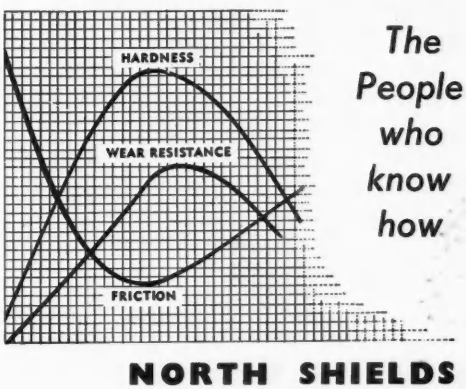

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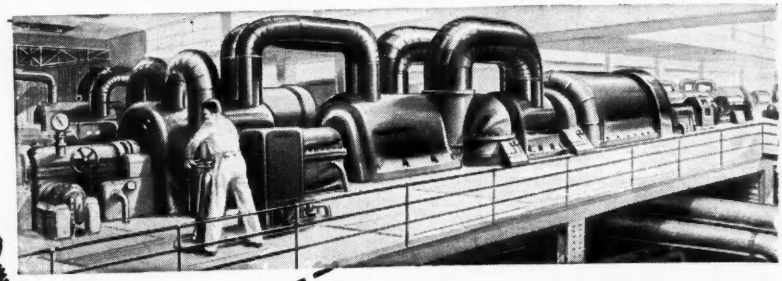

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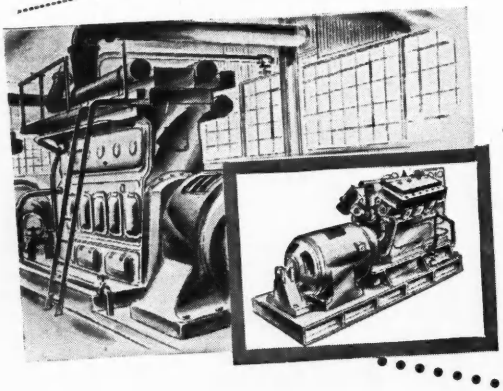

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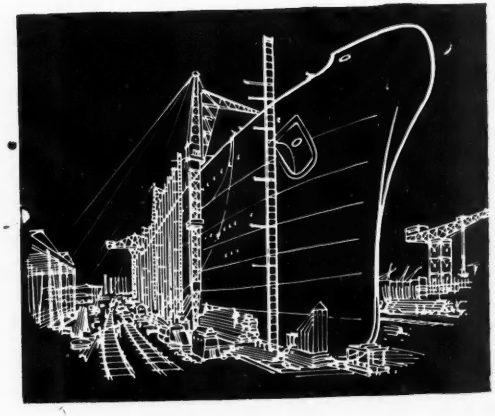

industry

ENGINEERING, MARINE & WELDING EXHIBITION AND THE FOUNDRY TRADES' EXHIBITION

OLYMPIA · LONDON · SEPTEMBER 1st to 15th, 1955

Organisers: **F. W. BRIDGES & SONS LTD.**

Grand Buildings, Trafalgar Square, London, W.C.2. *Tel.:* Whitehall 0568-9

The **Compoflex Co. Ltd.,** 26 Grosvenor Gardens, London, S.W.1, have opened a new experimental and development establishment at Godalming, Surrey. The new establishment will be in charge of Mr. J. Moseley, technical director, who will have the assistance of Mr. D. J. Saunders, chief development engineer (Hydraulics) and Mr. P. W. O'Brien, technical manager (special projects).

Head, Wrightson & Co. Ltd., Teesdale Iron Works, Thornaby-on-Tees, have acquired Colliery Engineering Ltd., Sheffield, and its subsidiary, the Cupola Mining and Milling Co. Ltd. Mr. Peter Wrightson has been elected chairman, Mr. L. W. Needham, managing director, and Mr. H. Cussons and Mr. S. A. Casson, directors of Colliery Engineering Ltd. Sir John Wr ghtson, Bt., has been elected chairman, Mr. A. Chilton, managing director, and Mr. Peter Wrightson, Mr. L. W. Needham and Mr. H. Cussons, directors of the Cupola Mining and Milling Co. Ltd.

The Zinc Development Association and its affiliates, the Hot Dip Galvanizers, the Zinc Alloy Die Casters and the Zinc Pigment Development Associations, have moved their offices from Oxford to new premises at 34 Berkeley Square, London, W.1. Tel. No.: GROsvenor 6636. The new offices will provide a centre for all who require rapid and up-to-date information on zinc and its uses.

The General Electric Co. Ltd., Magnet House, Kingsway, London, W.C.2, has acquired the Amalgamated Electric Corporation Ltd., Toronto, Ontario, Canada. Mr. A. V. Armstrong will continue as head of the Amalgamated Electric Corporation Ltd., which has a 200,000 sq. ft. factory in Toronto and a smaller plant in Winnipeg. Mr. Leslie Gamage, vice-chairman and joint managing director of G.E.C., Mr. D. G. W. Acworth, manager of the G.E.C. export department, and Mr. J. B. Taylor, managing director of The British General Electric (Canadian) Ltd., have been elected to the Board.

Crompton Parkinson Ltd. announce that a new three stories building is scheduled for completion by the end of this year to form an extension to the company's present Research and Development buildings at Chelmsford. In addition, several modifications will be made to existing premises, including the erection of an improved observation room for the High Power Testing Station which is one of the A.S.T.A. approved stations, and new open air testing areas will be constructed.

Waymouth Gauges & Instruments Ltd., Godalming, a subsidiary company of Smiths Aircraft Instruments Ltd., announce a new extension of approximately 5,500 sq. ft. of floor space to their factory. Mr. E. B. Moss is technical director and Mr. P. S. Firmin is works director of the company.

The Second International Powder Metallurgy Congress, sponsored by Dr. Paul Schwarzkopf, President of The American Electro Metal Corporation, Yonkers, N.Y., will take place in Reutte, Tyrol, Austria, from June 20 to June 23. Reutte was chosen again for the seat of this international seminar because Europe's largest powder metallurgy company, The Metallwerk Plansee, is located there.

The topic will be " High Temperature and Corrosion-Resistant Materials by Powder Metallurgy." So far, approximately 300 representatives from 17 nations have been registered as delegates, including over 30 scientists, industrialists and engineers from the United Kingdom.

The ferrous Powder Metallurgy interests of Metallwerk Plansee are represented in this country by George Cohen Sinteel Ltd., a subsidiary of The 600 Group of Companies.

Wiggin Nickel Alloys by Powder Metallurgy. A new publication, issued by Henry Wiggin & Company Ltd., describes the application of the powder metallurgy process to the production of wrought nickel and nickel alloys. An illustrated description of the manufacturing process is given, together with tables comparing properties of materials produced by powder metallurgy with those of alloys produced by conventional methods of melting, showing the advantages of the close control of composition inherent to the powder process.

Copies of the publication may be obtained from the Publications Dept. of the Company at Thames House, Millbank, S.W.1.

Arthur Trevor Williams Pty. Ltd., 16 Burlington House, Rissik Street, Johannesburg, South Africa, have been appointed sole agents for Brookhirst Switchgear Ltd. for South Africa, the Central African Federation and Portuguese East Africa.

Inspection Equipment, 19 Broad Court, Drury Lane, London, W.C.2, have been appointed sole agents for the Fedrex Portable Industrial X-Ray equipment, manufactured by Carl Drenck Electro-Technical Laboratories, Copenhagen.

Cambridge Instrument Co. Ltd., 13 Grosvenor Place, London, S.W.1, announce the formation of a Mechanical Thermometer Division at their factory at Friern Park, N. Finchley, London, N.12. Tel. No.: HILside 5016.

Burton, Griffiths & Co. Ltd., Mackadown Lane, Kitts Green, Birmingham 33, announce that their Nottingham office has moved to new premises at 18 Carrington Street, Nottingham. Tel. No.: 53201.

The First European Conference on Statistical Quality Control will be held in Paris on 11th, 12th and 13th July.

To the Conference, which is sponsored by the European Productivity Agency of the Organisation for European Economic Co-operation, will come statistical quality control experts from Belgium, France, Germany, Italy, the Netherlands, Sweden, the United Kingdom and the United States.

Statistical quality control, one of the most recently developed techniques of industrial management, has quickly gained prominence in modern industrial life, as it contributes towards lowering costs and improving the quality of products.

Further details on the conference and the complete programme may be obtained from national productivity centres or direct from the European Productivity Agency (Project 328), 3, rue André Pascal, Paris, 16e.

BRITISH STANDARDS

(*Copies of British Standards may be obtained from the British Standards Institution, 2 Park Street, London, W.1*)

Flexible polyvinyl chloride (PVC) extrusion Compounds B.S. 2571 : 1955 applies to certain polyvinyl extrusion compounds supplied as material for the manufacture of various products. In some cases, the products, e.g., electric cables, for which these compounds may be used are covered by other British Standards, in which quality is controlled by tests made on the finished product. The use of compounds complying with the British Standard under review does not necessarily ensure compliance of a fabricated article with the British Standard appropriate to such an article.

B.S. 2571 specifies Compounds with specified electrical properties and having a volume resistivity not less than 10^{13} ohm-cm at 23° C; Compounds with specified electrical properties and having a volume resistivity not less than 5×10^{8} ohm-cm at 23° C; Compounds for which the electrical properties are not specified. Each of these classes is sub-divided into types so that in all, 12 types of compounds are provided for.

The specification lays down requirements for composition, form and appearance of the compounds, together with limits for Tensile strength; Elongation at break; Volume resistivity at 23° C; Effect on polythene (increase in power factor); Softness; Water absorption; Cold bend temperature; Cold flex temperature before ageing; Deformation under heat; Volume resistivity at 60° 3; Electric strength at 23° C; Loss on heating; Water soluble matter; Heat stability; Fastness to daylight exposure; Colour bleeding and Degree of flammability. Methods of Test are given in the Appendices. Price 5/-.

Horizontal mild steel welded storage tanks. B.S. 2594 : 1955 relates to the design and construction of mild steel fusion welded horizontal storage tanks with dished and flanged ends complying with Table 4 of B.S. 1966 ' Domed ends for tanks and pressure vessels ' and also to tanks with unflanged outwardly dished ends. The sizes of tanks range from 3 ft 6 in. diameter by 4 ft. nominal length up to 9 ft diameter by 30 ft nominal length.

B.S. 2594 specifies requirements for tanks of adequate safety and reasonable economy, in a range of sizes to suit the requirements of user industries. These tanks are intended for the static storage of liquids which are not corrosive to mild steel.

The tanks are classified by dimensions instead of by capacities which has hitherto been the practice in the trade. The gross capacities of these tanks are given in the tables.

Tanks with flat ends and tanks with inwardly dished ends are not provided for and the standard does not relate to tanks on transport vehicles or to lined storage tanks. Price 4/-.

Radiographic examination of fusion-welded joints in thicknesses of steel up to 2 in. (B.S. 2600 : 1955). The increasing use of X-rays and gamma-rays for the examination of welded joints in a wide variety of constructions has made it desirable to issue some recommendations of a general character giving guidance on the application of these methods. The Standard is divided into the following four sections :

SECTION 1 : covers the general recommendations for all types of radiography within the scope of the Standard.
SECTION 2 : covers X-ray techniques for general application.
SECTION 3 : covers X-ray techniques for special applications.
SECTION 4 : covers gamma-ray techniques.

An appendix amplifies the statements contained within the various clauses. Price 4/-.

Code of Practice for Zinc alloy pressure die casting for engineering. CP. 3001 : 1955 has been prepared jointly with the Institution of Mechanical Engineers. Its objective is the establishment of recognized practices in the design, production and inspection of zinc alloy die castings, in order to ensure that the materials used, the procedures followed, and the design of the castings, shall provide a product that reliable in every respect.

Pressure die casting in zinc alloy permits the very rapid production of engineering and allied components and also intricacy of design. It has therefore obvious advantages when a component is required in large quantities. For engineering components however, mechanical properties and durability are important considerations, and for this reason the best features of design should be employed and optimum casting technique adopted.

Zinc alloy die castings will perform satisfactorily in service only if they are free from contamination by certain elements harmful to the mechanical properties and corrosion resistance. The Code, therefore, states that it is essential that these elements should not be present in higher proportions than those indicated in B.S. 1004 'Zinc alloys for die casting.' Price 5/-.

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LATEST INDUSTRIAL LITERATURE

1. Refractory Strainer Cores. Details are contained in a pamphlet of a range of refractory strainer cores with many advantages over conventional types of cores, including the following :—They do not erode or spall, and are unaffected by molten metal ; they do not collapse during pouring, and have high mechanical strength and low thermal expansion ; and they do not gas the metal.

It is claimed that the use of these cores gives greater control during pouring and improves foundry efficiency, without any significant increase in the cost of castings. Furthermore, as they are made to controlled specifications, a standard performance can always be expected.

2. Hermetically Sealed Instruments. A leaflet describes and illustrates a range of instruments which have been subjected to a special technique of hermetic sealing, in addition to, and allied with, normal anti-corrosion and anti-fungus treatment.

A full range of a.c. and d.c. instruments with 4- or 6-in. dials is available, in both projecting and flush patterns. The range includes moving-iron and moving-coil ammeters and voltmeters, electric tachometers, induction wattmeters, frequency meters, power-factor meters, and rotary synchroscopes.

3. Length-Control and Counting Equipment. In a well-produced series of leaflets, neatly bound into a loose-leaf folder, details are given of a comprehensive range of industrial counting and length-control equipment. Numerous models are available, including equipment suitable for automatic length control in the textile and wire industries. Furthermore, controllers can be supplied with a mechanical drive which resets at the end of each run ; with a remote drive which resets at the end of each run ; and with a remote drive for continuous or near-continuous processes.

Of the industrial counting equipment, the standard electromagnetic counter, which is sealed in a dust- and moisture-proof case, is supplied for a.c. or d.c. operation, standard voltages being 6 V, d.c. ; 32 V, a.c. ; 48 V, d.c. ; and 200-250 V, a.c.

4. Pulley-Mounted Centrifugal Fans. Details are given in an illustrated 4-page brochure of a range of pulley-mounted centrifugal fans which can readily be adapted to conform to any hand or discharge position. This useful feature is facilitated by means of interchangeable inlet and bearing sideplates, in conjunction with a one-piece casing.

These fans, which are fitted with oil-lubricated ball bearings, are rigidly constructed throughout for heavy operation and are eminently suitable for handling entrained dusts, fumes, or gases.

5. Slip Gauges. Manufactured by a firm who have been producing high-class precision gauges, form tools, etc. for over 35 years, the slip gauges described in a 4-page brochure are strictly in accordance with B.S.S. 888 and have been given special heat treatment to ensure absolute stability of size.

These gauges, which are available in workshop, inspection, calibration, or reference grades, are supplied in a range of sets, as required, each set being furnished complete in a well-finished wood cabinet.

6. Limit Switches. Good contacting is a vital consideration in any limit switch, however infrequently it may be used and, in a range of switches described and illustrated in an excellently produced 8-page booklet, this feature has been given particular attention. These switches have a double "make" and a double "break," and the contacts are of pure silver. Operating springs are long and are so lightly stressed that the possibility of spring fatigue is negligible. Four clamp-type cable terminals, accessible from above, are provided, and the moving parts of each switch are enclosed in a transparent insulating shield, as a protection against dust and inadvertent contact with the wiring.

Two patterns are available, i.e., slow action and snap action. In the slow-action pattern, the speed with which the contacts move is determined entirely by the speed of the operating plunger, while the snap-action pattern has a rapid movement, the speed of "making" and "breaking" being independent of the speed of the operating plunger.

7. Cathode-Ray Oscillographs. An 8-page illustrated booklet summarizes the working principles and shows numerous industrial and scientific applications of a range of cathode-ray oscillographs, comprising double-beam oscillographs and a miniature, portable oscillograph, the latter weighing only 9¼ lb and fitted with a tube of 2¾ in. screen diameter.

Cameras, specially designed for use with the double-beam models, are also available.

8. Machine Knives. A well-produced and illustrated pamphlet describes a comprehensive range of machine knives for a variety of purposes, including tobacco knives, cigarette knives (circular and scissor types), woodworking knives, textile-machinery knives, and packaging-machinery knives.

The range also includes paper knives, embracing circular paper and cardboard slitters, creasing knives, dished cutters, dead knives, doctor blades, and guillotine knives. In addition, there is a wide selection of metal-cutting blades, including shear blades in alloy steel for cutting sheet and plate, angle cutters, bar-cropping blades, and circular cutters for slitting cold-rolled strip.

9. Motors for Power-Station Auxiliaries. The successful operation of boiler plant in modern power stations depends very largely on the efficiency and reliability of the electric drives. For most power-station drives the squirrel-cage induction motor has been found to be the most suitable, as its simple construction greatly assists in achieving a rugged and reliable machine.

In a 12-page, illustrated publication, the subject of motors for power-station auxiliaries is dealt with both interestingly and informatively, providing as it does a wealth of concise information, illustrated by actual examples, on a subject of importance to users of boiler plant.

10. Spray-on Fibre Insulation. In a neatly produced 4-page brochure, details are given of a modern insulating material for thermal, acoustic, and decorative purposes. This material is a construction of mineral fibres and binder, which, by a special technique, is sprayed onto the surface to be treated. The process can be applied to any rigid surface of any contour, of brick, metal, concrete, plastic, wood, stone, or metal lath, producing a blanket-like surface containing a multitude of minute air pockets which entrap and absorb sound vibrations and which form a highly efficient barrier to thermal transmission.

A rubber-based adhesive is normally applied to the surface to be treated and, as there is no intervening mass of air, there can be no condensation on a metal surface. The material and the rubber-based adhesive also serve to protect metal from rust and corrosion, and can be used in high-temperature work.

11. Non-Sparking Tools. Representative examples from a very wide range of non-sparking tools are described and illustrated in a well-produced series of leaflets in a loose-leaf folder. The range includes one-piece pneumatic tools, crowbars, hammers of various types, picks and shovels, forks, hoes, wedges, and chisels.

These tools represent a very real safety precaution in localities where chance sparking may cause a serious fire or explosion.

12. Electrical Insulating Materials. An interesting and neatly produced 16-page booklet describes and illustrates a comprehensive range of electrical insulating materials consisting of silicone resins and elastomers in various combinations with glass fibre, mica, and asbestos. These materials vary from thin, flexible sheets and sleeving to rigid structural components, which may be more than 1 in. in thickness. The booklet also includes details of a range of insulating wires and power cables.

This range of silicone insulating materials has outstanding thermal stability, low dielectric loss, and other useful properties. The components have wide applications, varying from miniature electronic components to large transformers, motors, and switchgear.

13. Leather Packings for Hydraulic and Pneumatic Mechanisms. The practical aspects of hydraulic engineering, upon which relevant information has hitherto been somewhat scarce, are discussed in an excellent 80-page handbook, which includes chapters on hydraulic and pneumatic pressures ; application of leather packings ; impregnating and moulding ; leather ; design and support of packings ; cup, flange, "U," and "V" packings ; design of hydraulic cylinders, cylinder bottoms, glands, and gland rings ; common troubles ; storage and care of leather packings ; and hints for users of leather packing.

Also included are reference data, and altogether this profusely illustrated and well-conceived handbook should be of inestimable value to those concerned with leather packings in hydraulic and pneumatic applications.

14. Voltage Reference and Stabiliser Tubes. A wide and diverse range of electronic applications in industry, telecommunications, and research would not be possible without extremely stable d.c. voltage sources. At the heart of these stable voltages are voltage reference and stabiliser tubes, all of which must be accurate, reliable, and correctly chosen.

Entitled "A Guide to the Application of Voltage Reference and Stabiliser Tubes," a new 20-page illustrated booklet includes sections on the fundamentals of voltage reference and stabiliser tubes ; the interpretation of published characteristics ; and applications, including design formulae for associated components. This well-written and produced booklet should be invaluable to designers of equipment for use in these fields.

15. Portable Tool and Lighting Transformers. Details are contained in a series of leaflets of a range of compact, robust transformers, with single or multiple output connections to enable several tools and/or handlamps to be operated from one transformer. These gives a voltage of 25 V for lighting and 110 V for tools on a 230-250 V mains supply.

These transformers are of the double-wound, naturally air-cooled type, fitted with an earth shield between the primary and secondary windings. The complete unit is contained in a watertight sheet-steel case, fitted with carrying handles and a detachable, gasketed cover for access to fuses. Provision is also made for coiling cables around the carrying handle, when not in use.

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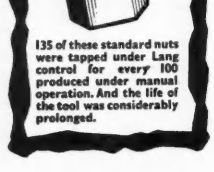
Over 500 leading industrial concerns in this country alone have found that the introduction of Lang Pneumatic Control Gear to a great variety of precision machines and industrial functions has allowed a great use of semi-skilled labour and speeded production on precision operations. It is simple to control, has the ability to withstand heavy, continuous operation, and offers a wide flexibility of application based on standard components. Every component of Lang Pneumatic Control Gear is made from stainless steel or non-ferrous metals and is entirely non-corrodible.



135 of these standard nuts were tapped under Lang control for every 100 produced under manual operation. And the life of the tool was considerably prolonged.

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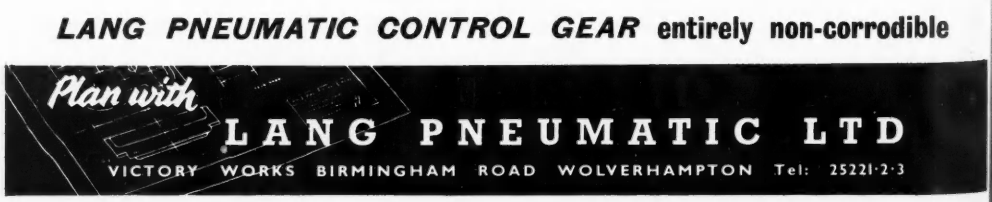

BOOKS RECEIVED

Conversion Factors and Tables. 2nd Edition, 1955. By O. T. Zimmerman, Ph.D. and Irvin Lavine, Ph.D. 525 pages. Publishers: Industrial Research Service Inc., Masonic Building, Dover, New Hampshire, U.S.A. Price: $5.50.

In the ten years since this extraordinarily useful book first appeared, it has more than proved its worth, not only in the U.S.A., but throughout the world. This new, enlarged, and completely revised edition, with over 12,000 conversion factors and 122 pages of conversion tables based on the latest and most accurate data, is the direct outcome of a number of changes in the values of important physical constants.

At the same time, the book has been enlarged by the inclusion of considerable new material. Among other features of this new edition are an expanded conversion-factor section, a section of foreign monetary equivalents, an expanded conversion-table section, a table of physical constants, and the inclusion of 5-place logarithms, e.m.f.-temperature conversions for a number of thermocouples, hardness conversion factors, wire and sheet-metal gauges, conversion factors for the principal viscometer scales, and colour-scale conversions for liquids. Incidentally, not the least fascinating thing about this excellently printed and well-presented work is the section devoted to conversion factors for most of the countries of the world, with a wealth of interesting and exotic measures ranging from a Caffiso to a Chitak and a Kwak to a Kontang.

For engineers, physicists, and, indeed, for all technical men, this book should doubtless prove of inestimable value.

The Wire Industry Encyclopaedic Handbook, 1955. 495 pages. Publishers: The Wire Industry Limited, 33 Furnival Street, London, E.C.4.

This new edition of the Encyclopaedic Handbook will, like its predecessors, be of great use to all connected with wire drawing and the wire-fabricating industry. In addition to a trade summary for 1954, sections are devoted to a variety of subjects connected with the industry, including an alphabetical index to advertisers, a buyers' guide to supplies, which is a complete list, alphabetically arranged by products, of manufacturers and suppliers of plant and equipment, and a branded-names section identifying manufacturers with brand names in common use in the wire trade.

In addition, the book includes a short selection of articles on processes, equipment, etc., and the popular encyclopaedia, which is an alphabetical reference section of technical and commercial terms in mills, workshops, and offices.

British Plastics Year Book, 1955. 652 pages. Publishers: Iliffe and Sons Ltd., Dorset House, Stamford Street, London, S.E.1. Price: 30/-.

This 25th edition has been revised and extended. It is divided into nine sections, three of which are devoted to classified lists of manufacturers and suppliers of materials, finished products, and equipment. Another section contains the world's largest list of trade and proprietary names connected with the plastics industry, and covers materials as well as finished products. Each trade name is followed by a definition of the product, the manufacturer concerned, and, where the manufacturer is overseas, the country of origin. A glossary of technical terms used in plastics is again included in this section. The names and addresses of nearly 4000 firms associated with plastics are grouped into countries in the Names and Addresses section. In addition, the "Who's Who" section lists names and positions of prominent people in Britain's plastics industry.

One of the most important features is the annual review of plastics patents. This section of 139 pages contains all relevant patents issued last year, collected, abstracted, and arranged in subject groups. Each group is abstracted by experts, and prefaces give a brief review of the year. The Patent Abstracts section therefore provides an invaluable record of technical developments as shown in the patent literature.

A list of new plastics companies registered during 1954, providing details of the official date of registration, address, activities, capital, and directors, is included, together with a general index giving quick reference to any product or subject in the book.

Strength and Resistance of Metals. By John M. Lessells. 464 pp., 208 illustrations. Publishers: John Wiley & Sons, Inc., N.Y., and Chapman & Hall Limited, 37 Essex Street, London, W.C.2. Price: 80/-.

As the author points out in his preface, the design of machine elements is no longer based on empirical relations; rather, analytical methods involving advanced theory have become more common in solving engineering problems. However, these more exact solutions can be usefully applied in design only if information is available on the manner in which engineering materials behave under applied stress.

The aim of this well written book on the strength and resistance of metals is to provide senior and graduate students, as well as design engineers, with information on the behaviour of metals under stress, as revealed by numerous workers in this field. This information includes some of the author's contributions, drawn from many years of experience in different fields of mechanical engineering. Most of the discussion centres around steel, but mention is made of non-ferrous alloys and cast iron in those particular instances where their behaviour differs from that of steel.

The book includes a number of illustrative problems, together with additional problems relating to the subject matter of each chapter. Altogether, this volume should be of undoubted interest and value not only to teachers and students, but also to practising engineers.

100 YEARS OF ALUMINIUM AS AN ENGINEERING MATERIAL

The Supplement on the centenary of Aluminium as an Engineering Material, appearing in this issue of "The Engineers' Digest," will be published as a separately bound 48-page booklet and will be available at 4/6d. per copy.

Orders for copies of the booklet should be sent to Sir Isaac Pitman & Sons Ltd., Parker Street, Kingsway, London, W.C.2., who have been appointed sole distributors of the publication.

CONTRACTS

The General Electric Company Limited has received from its Australian associate, The British General Electric Company (Pty.) Limited, an order for an automatic electric winder for Mount Isa Mines Limited to be installed in their Queensland, Australia, mine. The winder will be a double drum type having drums 16 feet in diameter and will be driven through reduction gears by two 2,250 h.p. D.C. motors.

The equipment is designed for a final duty of raising 12 tons of ore per wind by skips from a depth of 4,000 feet, giving an output of 350 tons per hour.

Automatic pushbutton control from twelve different levels will be provided, and the control scheme will incorporate G.E.C. control exciters operating in conjunction with a Ward Leonard Ilgner set driven by a 3,350 h.p., 3.3 kV slipring motor. The contract includes the driver's control desk together with all the associated A.C. and D.C. switchgear and motor control gear and is valued at approximately £A200,000.

Classified Advertisements.

The rate for all classified advertisements is 6d. per word; in bold print 9d. per word; minimum order 6s. Box-number advertisements 1s. extra. Instructions, together with remittance, must be received not later than the 3rd of each month for advertisements to appear in the same month's issue.

UNIVERSITY OF BIRMINGHAM
Department of Mechanical Engineering
Graduate School of Thermodynamics and Related Studies

A course available in the above School provides facilities for the study, at advanced level, of modern developments in Thermodynamics and allied subjects and of their applications in the general field of the heat engine. The normal entrance qualifications are an Honours Degree in Mechanical Engineering together with a minimum of two years of practical experience in industry. On completion of the twelve-month course commencing on the 3rd October, 1955, and including nine months attendance at the University, successful candidates qualify for the award of the degree of Master of Science. In special circumstances applications may be considered from the graduates in other Sciences holding satisfactory alternative qualifications. In the latter case it will usually be necessary for two years to be spent in completing the course. The award to successful non-graduate engineers is the Diploma of Graduate Studies.

The inclusive fee for the course of study is £71 1s. 0d. In certain cases where a student is not sponsored by an employer, the University may consider applications for the remission of this fee and, where essential, for the grant of a maintenance allowance during the period of attendance.

Further particulars and application forms may be obtained from he Registrar, The University, Edgbaston, Birmingham, 15.

G. L. BARNES, *Secretary.*

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PERMANENT STAFF APPOINTMENTS await young Graduate Engineers with good Honours Degrees. The Wilton Works Site of 2,000 Acres, in course of development, in addition to providing general and varied experience in modern Engineering, has its own special problems in design and materials.

The organisation is expanding and has opportunities for technical training followed by further training towards higher management.

Situated in the North Riding of Yorkshire, near the coast, Wilton offers first-class working conditions, five-day working week, Pension Fund and full recreational facilities.

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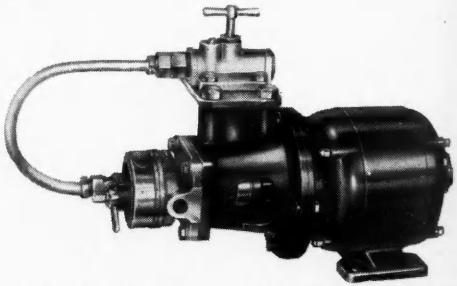

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A QUICK GLANCE AT THE LATEST TECHNICAL DEVELOPMENTS THROUGHOUT THE WORLD

● *PUMPING DEVICE FOR CIRCUIT-BREAKERS*

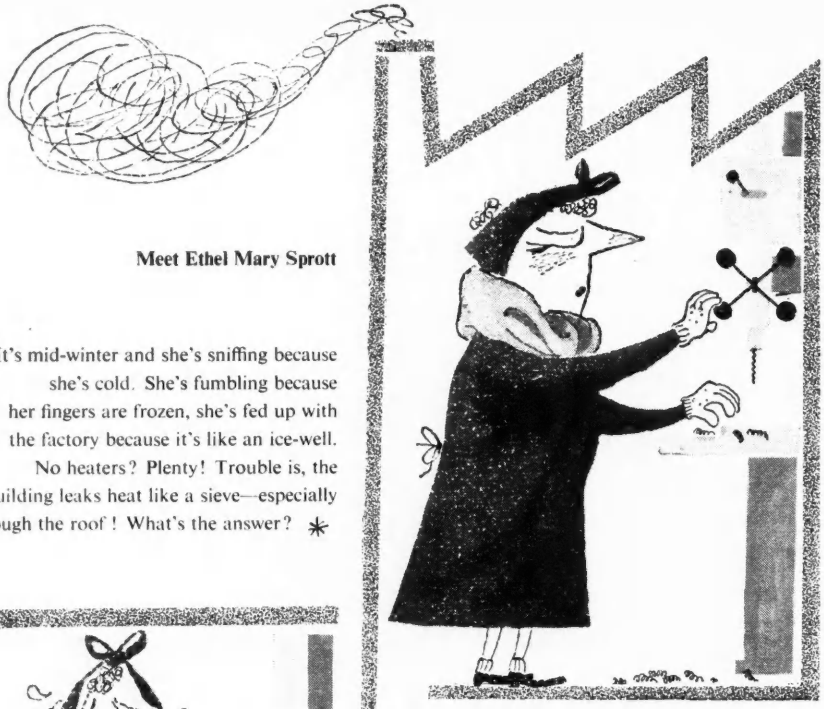
A recent patent specification describes a novel type of pump for circuit-breakers which can form part of the electrical conductors and can be operated by the current passing through the latter. This pump comprises a slotted, resilient cylinder of magnetic material, traversed by a magnetic field. When an alternating magnetic field is set up in the cylinder, it will cause oscillatory variations in cylinder volume, so that the liquid to be pumped will be drawn into the cylinder or will be expelled from it, according to whether the cylinder is expanded or contracted. Thus, if the magnetic field is generated by a current of 50 cps, the cylinder is oscillated at a frequency of 100 cps and its volume changes at the same frequency. Consequently, liquid will be forced out of the cylinder through the slots and will be drawn into the cylinder in synchronism with the alternating current. The slots in the cylinder are closed by flaps, which act as non-return valves, so that the liquid can flow only from the interior of the cylinder through the slots to the exterior, while the liquid is admitted to the cylinder through another set of non-return valves. If the magnetic field is generated by a hollow conductor extending through the cylinder, the conductor can be made to act simultaneously as an inlet and outlet conduit for the pump. It will be appreciated that the volumetric output of a pump of this type is necessarily small, but it will be sufficient to provide a sufficiently large flow of oil for arc-quenching purposes, such as is required in circuit-breakers handling currents of great magnitude.

● *AUTOMATIC WELDING METHOD*

A new method of welding, which eliminates the skill normally required, is now available. It is claimed that this method does away with all the difficulties encountered with conventional welding methods of acquiring the necessary skill of manipulating the welding electrode and of controlling the arc. The new method employs a special welding electrode and electrode holder. To make a weld, the tip of the electrode is merely held against the metals to be joined at the point where the weld begins, a switch on the holder is pressed to fire the electrode, and the electrode, as the tip is held against the metal, automatically makes the weld itself. The electrode and holder normally do the work required of the welding operator. Locating the beginning of the weld, starting the arc, feeding the electrode, and maintaining the electrode angle and travel speed are controlled automatically by the design of the electrode and holder. A supporting leg on the holder can be used to help locate and steady the electrode on the joint and to control the angle of the electrode. The coating of the electrode touches the work at all times, so that arc length is automatically determined. The melt-off rate automatically controls the welding speed. It is claimed that excellent welds can be made at the first attempt.

● *PLASTICS FOR USE WITH STRONG NITRIC ACIDS*

A significant increase has been registered in the use of plastics and synthetic elastomers as a container material for concentrated and fuming nitric acids. The ethylene family of plastics is generally the most resistant to nitric acid. There are many good reasons for using these plastics as liners for nitric acid containers. Thus, for instance, a plastic liner permits the use of less costly and more readily available metal for the container structure. Moreover, a plastic liner makes possible the use of lightweight structural vessels—an important factor in aircraft and guided-missile applications. Another important factor is that plastic liners retard sludge and crystal formation in stainless or aluminium vessels. The three plastics materials resistant to nitric acid are polyethylene and the fluorocarbons Teflon (Fluon) and Kel-F (Fluorothene). These materials vary in their resistance to concentrated and fuming nitric acids. Polyethylene is suitable for the handling and storage of strong nitric acids for short periods of time, after which it is attacked and fails. Irradiated polyethylene, recently developed, is reported to have a higher melting temperature and tensile strength than the regular product because of cross-linking of the polymer by exposure to radiation. It is considered probable that irradiated polyethylene also has improved nitric acid resistance. Fluorocarbon plastics are not attacked by nitric acid in any concentration. However, after some time in fuming acids, these materials become somewhat permeable to acid and oxide vapour and lose some of their usefulness as liner materials. A plastics/glass-fibre sheet with a Kel-F film on one surface represents a recent development; the reinforced plastics offer structural strength, while the interior Kel-F lining renders the container resistant to nitric acids.



Meet Ethel Mary Sprott

It's mid-winter and she's sniffing because she's cold. She's fumbling because her fingers are frozen, she's fed up with the factory because it's like an ice-well. No heaters? Plenty! Trouble is, the building leaks heat like a sieve—especially through the roof! What's the answer? *

Meet Ethel Mary Sprott

It's mid-summer and she's sweating and swearing because she's hot. She's getting careless because she's drowsy. She's fed up because the factory's like an oven. What's the trouble? No windows or fans? Not on your life! Feel that roof. It's *baking* hot. No wonder production is slacking off. So what? So . . *

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● *TITANIUM NITRIDE ELECTROLYTIC CONDENSER*

A recently issued patent envisages important improvements in the production of electrolytic condensers moulded into or embedded in thermoplastic or thermosetting insulating material. Plastic-moulding processes may involve temperatures of the order of 160° C and pressures of the order of 600 psi. One object of the invention, therefore, is to provide an electrolytic condenser which will withstand such pressures and which will have a very flat shape, while having a high coefficient of capacitance approximating 1 microfarad per sq in. The main feature of the proposed condenser is that one of the condenser plates consists of titanium metal, one surface of which is converted into titanium nitride, while the other condenser plate is made of aluminium sheet. The electrolyte is placed between the titanium nitride surface and the aluminium plate. A very simple process is adopted for providing one surface of the titanium sheet with a layer of titanium nitride and consists of heating the titanium metal in a nitrogen atmosphere. It has been found that, up to 800° C, a firmly adherent layer of titanium nitride is formed in this way upon the surface of the titanium sheet, and that this layer will not be damaged or loosened by the subsequent press-moulding operation. Upon the titanium nitride layer is placed a sheet of paper containing the electrolyte, such as a mixture of glycol and triethanolamine borates. On top of the processed paper is mounted an aluminium foil constituting the other plate of the condenser. This assembly is housed in a casing consisting of two sheets of styrenated paper, which are lightly heat-sealed at the edges.

● *BOMB-BLAST SIMULATOR*

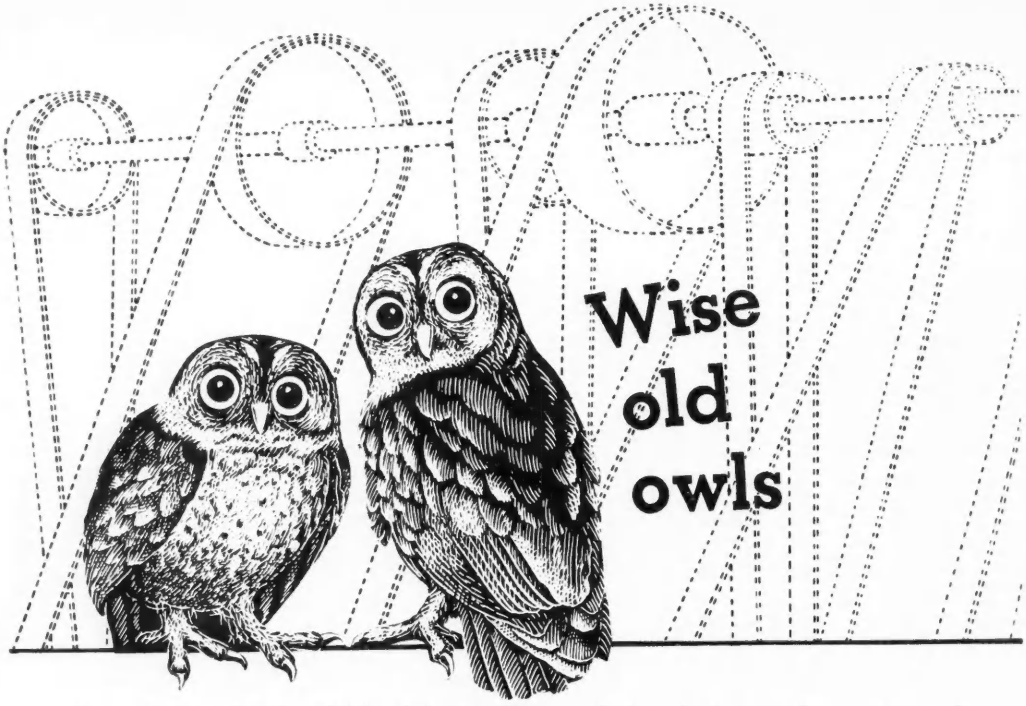
A device has been developed for simulating the blasts from bombs. This device—a shock tube—makes it possible to investigate the effects of blasts without actually exploding a bomb. The new shock tube has a diameter of no less than six feet, and is therefore appreciably larger than any devices of this kind previously constructed. The significance of a shock tube of this size lies in the fact that it enables research workers to study blast effects on structures of considerable size. An idea of the magnitude of this installation will be gained from the fact that the length of this shock tube is about 150 ft. In order to produce shock waves of different pressures, provision is made for the insertion of interchangeable sections of varying lengths. To absorb the maximum recoil force of 600,000 lb, the foundation of the tube was designed as a slab of reinforced concrete 10 ft wide, 3 to 4 ft thick, and 100 ft long, with keys, 10 ft wide and 6 ft deep, spaced 20 ft apart. Operation of the shock tube is comparatively simple. A quantity of combustible gas is introduced into one section of the tube, where it is confined by a light diaphragm. The diaphragm is shattered when the gas is ignited by an electric spark, and the released pressure wave travels down the tube to the test section where the model of the structure to be tested has been placed.

● *BONDING OF ELECTROLYTICALLY DEPOSITED TIN LAYERS ON STEEL*

It is known that the glossiness and corrosion resistance of electrolytically tinned iron sheets can be improved by heating the sheet after electrolysis for a short period to a temperature above the melting point of the tin and then rapidly cooling it. Extensive systematic examination has shown that this melting-on process has certain disadvantages. In the short-period melting-on of the tin coating, the tin layer is not uniformly distributed, but runs together in places, forming an undulating surface, i.e., a large number of individual agglomerations of tin with areas in between only slightly coated with tin. These agglomerations of the liquid tin layer are accentuated by the fact that part of the hydrogen absorbed during the pickling and coating processes escapes during the melting-on process and thus inflates the liquid tin layer. Another adverse factor is that residues of the electrolytic liquid and of the acid accumulate in the coating and cannot be removed to a sufficient extent by washing and drying the sheet after electrolysis. As a result, vapour is formed in the liquid tin layer, and, owing to this generation of gas, crater-like cavities are formed in the surface of the tin. In a newly patented process glossiness and corrosion resistance of the sheet are obtained by melting-on the tin layer in two successive stages of induction or resistance heating. In the first stage, the sheet is heated to a temperature below the melting point of tin, to remove residual gas or liquid present; in the second stage, the sheet is heated to a melting-on temperature above the melting point of tin.

● *ELECTROLYTIC CELL FOR TITANIUM PRODUCTION*

An interesting proposal has been made concerning the electrolytic production of titanium by a plating process. This novel method is based on the use of an electrolytic cell which plates titanium onto a wire or rod of titanium. A starting wire is inserted into the cell and, as titanium builds up by electrodeposition on the wire, the latter is withdrawn continuously. In the original cell built to prove the feasibility of the principle, some 50 grams of titanium were produced in rod form per day. As a next step a cell, producing one pound of titanium per day, was constructed. It is intended to build more powerful cells, producing 10 lb and 50 lb of titanium per day respectively and, after sufficient operating experience has been gained with these installations, the construction of commercial units, capable of



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producing one-half to one ton of titanium per day, will be undertaken. The cell, which uses an inorganic electrolyte operating below 400° F, is kept at normal pressure and does not require an inert atmosphere. Cathode efficiency is claimed to be approximately 98%. For the original 50-gram cell, pretreated rutile, containing 95% titanium oxide, was used as the feed material. In order to reduce cost, ilmenite or titanic iron ore, containing 54% titanium dioxide, is now being tried in place of the more expensive rutile. Rods up to $\frac{3}{8}$ in. in diameter have already been produced in the 50-gram unit, and it is reported that no electrical or mechanical considerations, other than the physical size of the cell itself, appear to set a limit to the diameter or thickness of the titanium plate on the starting metal. The purity of the metal obtained is claimed to be 99·7%, with a power consumption of approximately 9·4 kWh per lb of titanium produced.

● *NEW TYPE OF INTERFERENCE-FREE FLUORESCENT LAMP*

A fluorescent lamp of the cold-cathode type, which is essentially free from radio interference, has recently been developed. Various attempts have been made to reduce to acceptable levels interference from fluorescent lamps of the hot-cathode type. These attempts have resulted in the addition of radio-interference filters in the power-input leads of the lamp and, in some instances, the use of transparent conducting materials. Recent experiments have utilized a coating which can be applied to ordinary transparent plastic materials. It is stated that this arrangement has produced excellent results in reducing radio interference. A study of a ceiling fixture and three sets of cold-cathode fluorescent lamps was made, the sets of lamps differing in their internal gas pressures. The fixture included four lamps containing a dual ballast and was designed for recessed installation in the ceiling. Measurements were made of the radio interference generated during normal operation. The frequency range covered was 150 kilocycles to 100 megacycles. The internal wiring of the lamp fixture was modified in order to obtain maximum reduction of radio interference. Test results indicated that the set of modified lamps operated with a dual ballast was within the prescribed limits for both radiated and conducted interference. When a high-voltage transformer was substituted for the standard dual ballast, interference levels were further reduced. It was ascertained that the radio-interference levels in these cold-cathode lamps fall off rapidly as frequency increases and do not exceed five microvolts above five megacycles. Use of this type of cold-cathode lamp makes capacitors or filters unnecessary in the fixture, and does away with the interference characteristics of starter mechanisms, which are used with hot-cathode lamps but which are not required with cold-cathode lamps.

● *NEW POLYESTER RESIN*

A new polyester resin has been developed which can be reacted with di-isocyanates to form a number of various plastic products with a wide range of properties. These new polyesters are essentially linear esters of adipic acids and glycols. The various formulations possible with isocyanates result in plastics with softening points ranging from 180 to 300° F, and solid elastomers, rigid and flexible foams, as well as lacquers and adhesives, may be produced as required. At present, the group of solid rubber-like materials developed is limited to cast forms in both hard and soft types, with excellent oil and abrasion resistance. Their comparatively high cost limits their application to products where these two special properties are essential. Both rigid and flexible foamed materials can be produced with polyester-isocyanate combinations. The reaction between the two resins produces carbon dioxide as the expanding agent. It is reported that one of the most important properties of this group is its capacity for close density control through adjustment of the amounts of isocyanate and other ingredients used in the reaction. Open- as well as closed-cell types can be produced, with densities ranging between 1 and 2 lb per cu ft and as much as 30 lb per cu ft. For thermal insulating purposes a low density of $1\frac{1}{2}$ lb per cu ft is used, while for structural purposes a density of some 8 lb per cu ft is chosen. Rigid foams are stated to have high compressive strength and excellent adhesion to most structural materials. Flexible foams may be made in large blocks or can be split into thin sheets on standard leather-splitting machines. Air-drying lacquers of high lustre and extreme toughness can also be produced.

● *POROUS METAL SHEET*

By means of a patented process, porous metal sheet can be made from a wide range of materials, e.g., austenitic steel, nickel, monel metal, and aluminium. The metal or alloy powder is deposited in a flat layer of uniform thickness, the particle-size range of the powder being selected to provide the final pore size desired. No binder is used at any stage of the process. The layer of powder is then passed through a furnace, where it is subjected to a temperature just below the melting point of the metal or alloy. At this temperature bonds develop at points of contact between adjacent particles, probably as a result of the migration of layers of atoms. Where stronger porous sheets are required, two alternative techniques may be used :—In the first of these, a sintered sheet is compressed by a calendering operation and resintered to develop additional bonds at the new contact areas. Such a calendered sheet retains a uniform pore size, but has less passage area than an uncalendered sheet of the same pore size. In the second method a perforated metal backing plate is applied to a sintered sheet.

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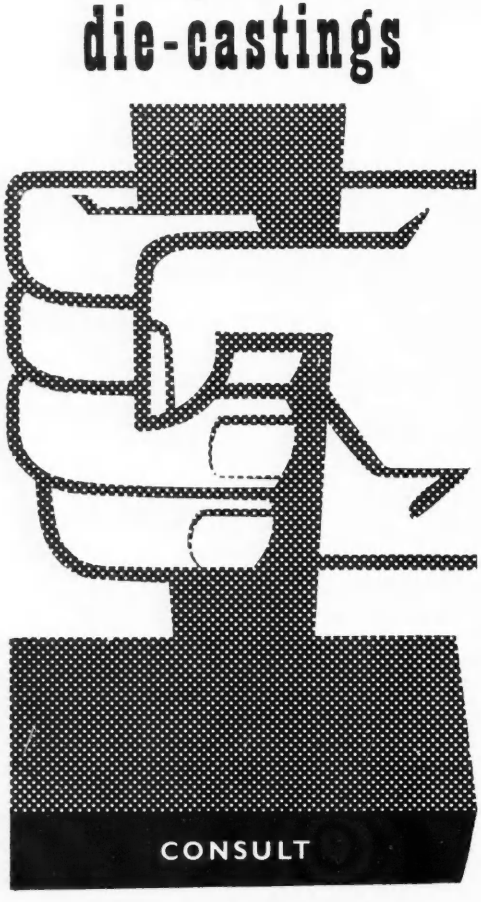

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This is effected by laying the sintered sheet on a perforated plate of similar composition and welding the assembly together by passing it through the sintering furnace. A correctly selected back-up plate will not appreciably change the flow capacity. For transpiration cooling, the sheet may be made from woven wire cloth instead of metal powder. By passing the cloth through a sintering furnace, the warp and woof strands are welded together; the rigid cloth is then calendered to reduce pore size and is finally annealed.

● *NEW ALUMINIUM-CERAMIC BOND*

There exist, of course, many methods of sealing non-conductors to metals, but none of these methods is used to form high-temperature hermetic seals with aluminium and its alloys. With the increasing use of aluminium in the electrical industry, the problem of joining aluminium to other metals and to non-conductors such as ceramic materials has become of considerable importance. This problem has now been solved by the development of a process which involves the use of either titanium or zirconium hydride to coat the ceramic surface with elemental titanium or zirconium, to which filler materials can alloy and bond the metallic component. This process is versatile and can be used with either soft solder or high-temperature brazing alloys. In a typical application, zirconium hydride is painted on the ceramic from a liquid suspension. After the liquid has evaporated, leaving a film of zirconium hydride approximately 0·001 in. thick, a ring or washer of a solder such as pure silver is placed around the painted area. The assembly is then placed inside a tantalum heat shield and a bell-jar is used to apply a vacuum of one micron or less, while the entire assembly is heated by induction coils. The zirconium hydride breaks down at around 900° F, leaving elemental zirconium on the ceramic surface, while nascent hydrogen is pumped out of the vacuum system. As heating is continued the silver melts, wetting and alloying with the zirconium. The next step consists of applying molten aluminium to the coated surface, with which the aluminium then alloys, producing a sound dendritic structure.

● *CALCULATION OF TEMPERATURE DISTRIBUTION IN CUTTING METALS*

The cutting of metals involves large inelastic deformations, most of the energy appearing as heat released over the shear plane. Assuming that the rate and distribution of heat release are known, the calculation of shear-plane temperatures is a complex heat-conduction problem involving a moving-band heat source, inclined to its direction of travel, and losing heat both to the workpiece and chip, the latter moving in a direction different from that of the workpiece. It appears that drastic simplifications are required before a mathematical solution may be obtained. A recent report describes an analytical approach to the problem, avoiding previous simplifications, which are considered to introduce considerable error, but introducing a new simplification. The simplification proposed consists of neglecting the transfer of heat by conduction in workpiece and chip in the direction of their respective motions, in comparison with the heat transferred by material transport in those directions and the heat conducted in the direction perpendicular to the direction of motion. This assumption results in considerable mathematical simplification and greatly facilitates analytical treatment. While this assumption is a common and understandable one in the study of heat transfer in a flowing fluid, it seems unusual when the moving medium has the high thermal conductivity of a metal. In order to estimate the magnitude of the error introduced by the simplified treatment, a comparison was made with a more rigorous mathematical solution, which included the effect of heat conduction in the direction of motion. This comparison, however, revealed satisfactory agreement.

● *SELECTIVE SEPARATION PROCESS, USING CRYSTALLINE ZEOLITES*

It has been announced that, with the development of two selective adsorbents, a completely new basis has been established for the separation of mixtures of liquids or gases. These adsorbents, which can be called "molecular sieves," are manufactured crystalline zeolites and have the outstanding property of adsorbing molecules below a certain diameter and passing all molecules which are larger. These sieves are heated during manufacture to drive out the water of hydration. The unique nature of the material prevents its collapse under heating, as distinct from other zeolites. A porous crystalline structure remains, containing an enormous number of cavities interconnected by millions of pores of extremely uniform size. Only the interior surfaces of the cavities are adsorptive; hence, only those particles (molecules) small enough to pass through the pores will adhere to the crystal. Besides exhibiting size selectivity, molecular sieves show a marked affinity for both polar and unsaturated molecules, in preference to non-polar or saturated molecules of the same size. Gas drying may be expected to become one of the outstanding applications of molecular sieves. Another potentially large use for these materials is the drying and purification of liquids. Molecular sieves also exhibit high adsorptive capacity at high temperatures. They will adsorb water at temperatures as high as 212° F, thus making it possible to dry gases at this temperature rather than having to precool the gas first. Another result of this strong affinity for water is that they can be used to dry gases to dew points below —100° F. At the present time two different materials, with pore sizes of four and five Angstroms respectively, are available.

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